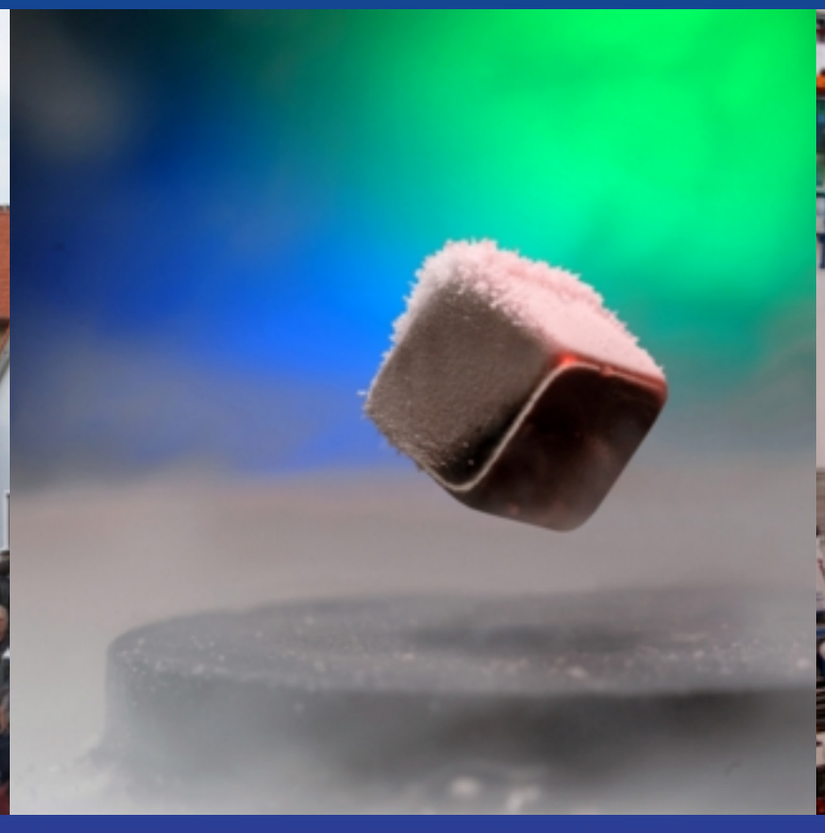
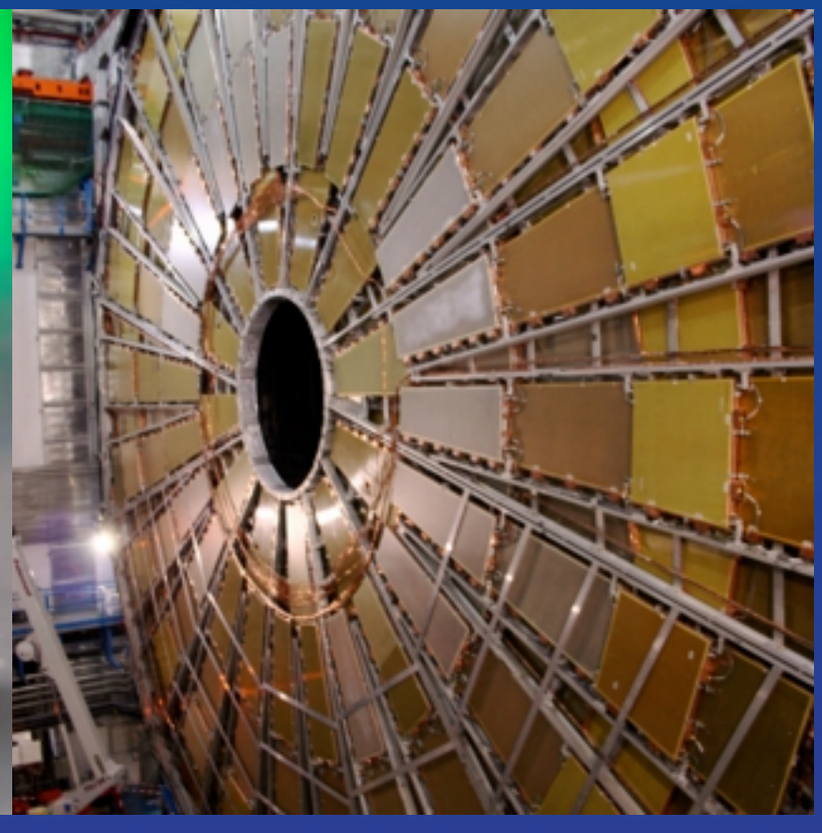
The Coming Revolutions in Particle Physics

Chris Quigg
Fermi National Accelerator Laboratory





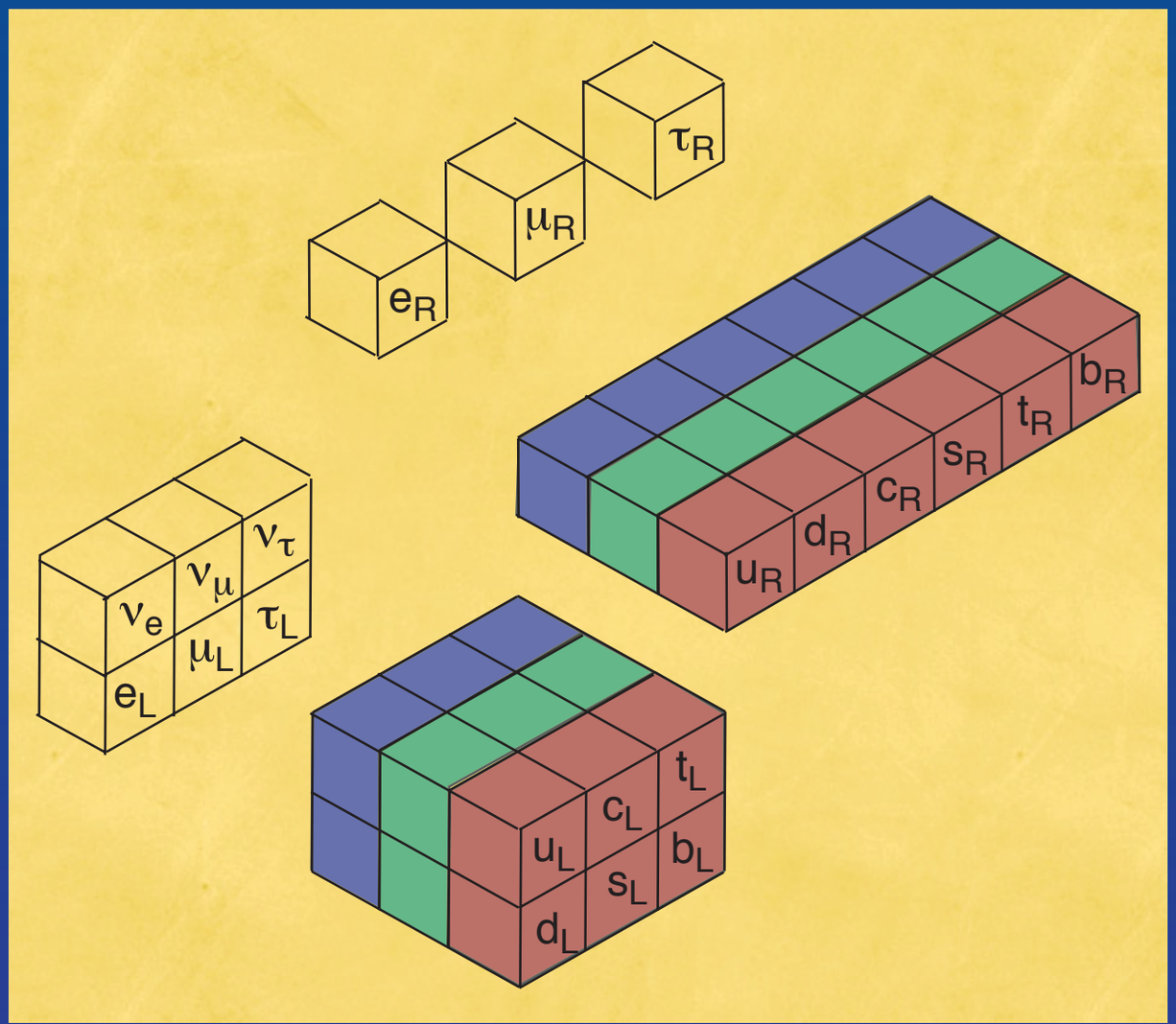
University of Michigan Colloquium · 3 February 2010

A Decade of Discovery Past

- ▷ Electroweak theory $\longrightarrow$ law of nature [Z, e^+e^-, $\bar{p}p$, νN, $(g-2)_\mu$, ...]
- ▷ Higgs-boson influence observed in the vacuum [EW experiments]
- ▷ Neutrino flavor oscillations: $\nu_\mu \longrightarrow \nu_\tau$, $\nu_e \longrightarrow \nu_\mu/\nu_\tau$ [$\nu_\odot$, ν_{atm}]
- ▷ Understanding QCD [heavy flavor, Z^0, $\bar{p}p$, νN, ep, lattice]
- ▷ Discovery of top quark [$\bar{p}p$]
- ▷ Direct CP violation in $K \longrightarrow \pi\pi$ decay [fixed-target]
- ▷ B-meson decays violate CP [$e^+e^- \longrightarrow B\bar{B}$]
- ▷ Flat universe dominated by dark matter & energy [SN Ia, CMB, LSS]
- ▷ Detection of ν_τ interactions [fixed-target]
- ▷ Quarks & leptons structureless at TeV scale [mainly colliders]

Our Picture of Matter (the revolution just past)

Pointlike ($r \leq 10^{-18}$ m) *quarks* and *leptons*



Interactions: $\mathrm{SU}(3)_c \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$ gauge symmetries

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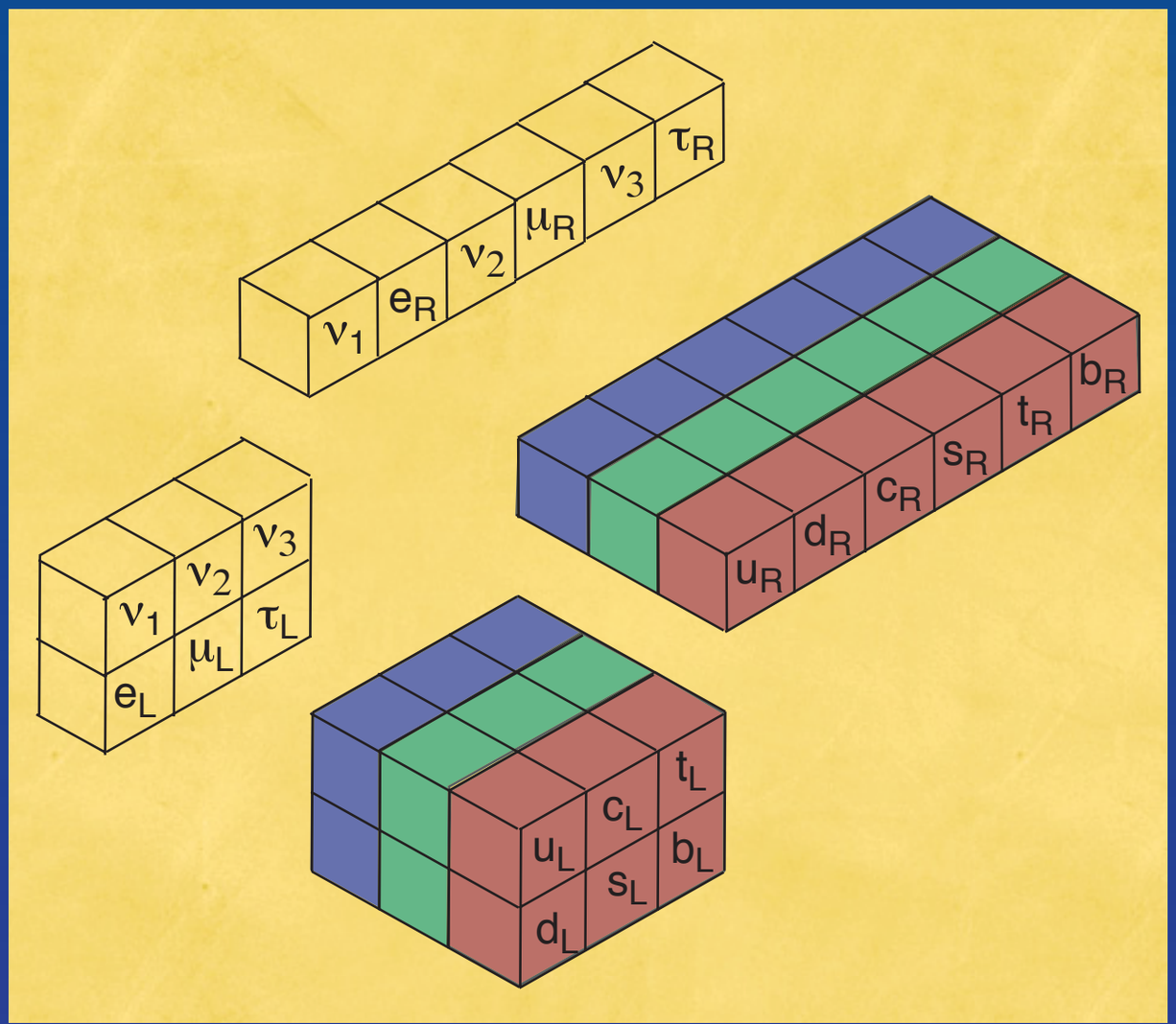


Interactions: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries


CDF
CQ
D0

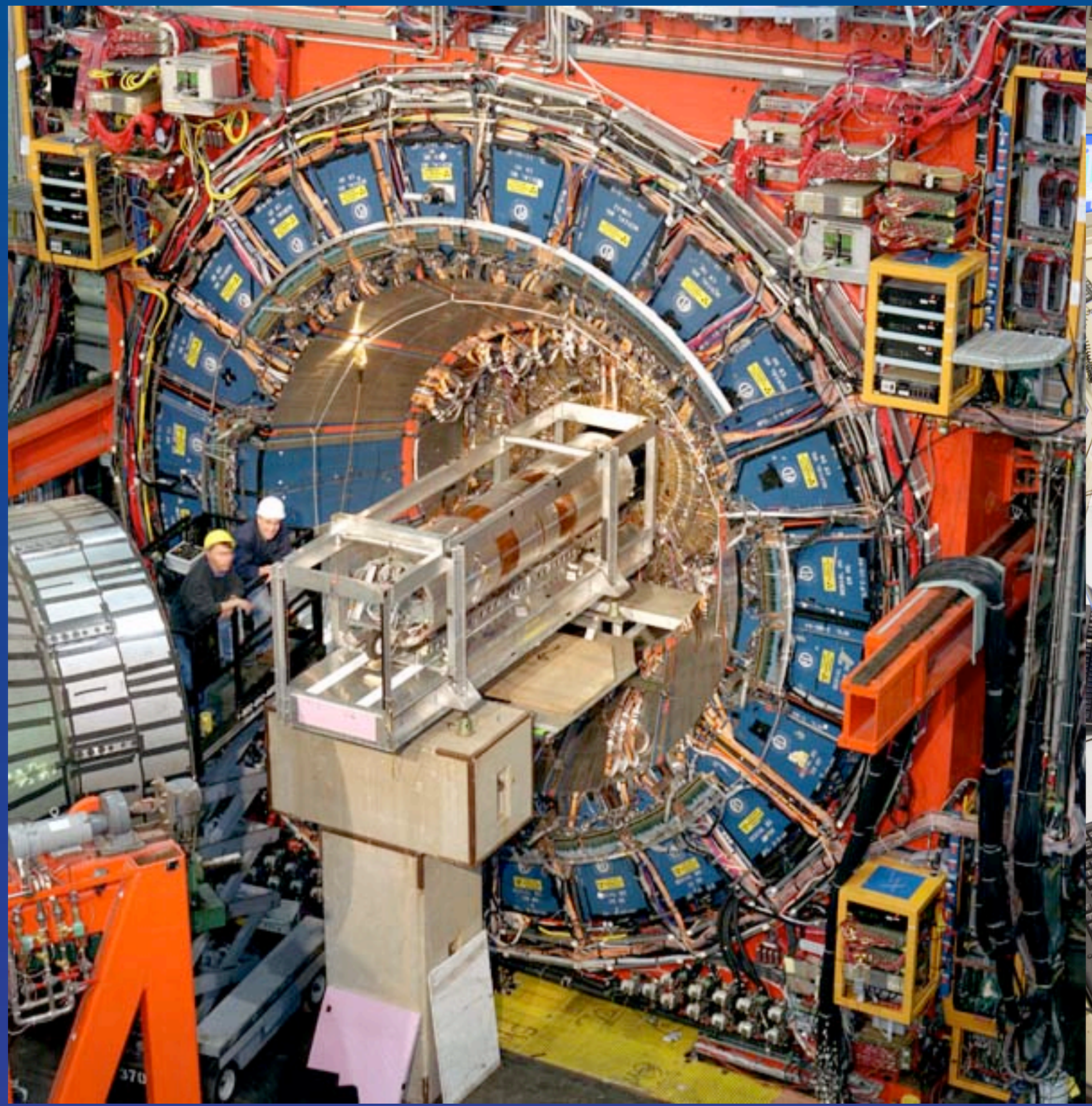
The world's most powerful microscope
… home to *nanonanophysicists*!

Tevatron collider at Fermilab
protons on antiprotons at 1+1 TeV
speed of light: $c \approx 10^9$ km/h
speed of protons: c – 495 km/h

Protons pass my window 45,000 times / second
>10 million collisions per second

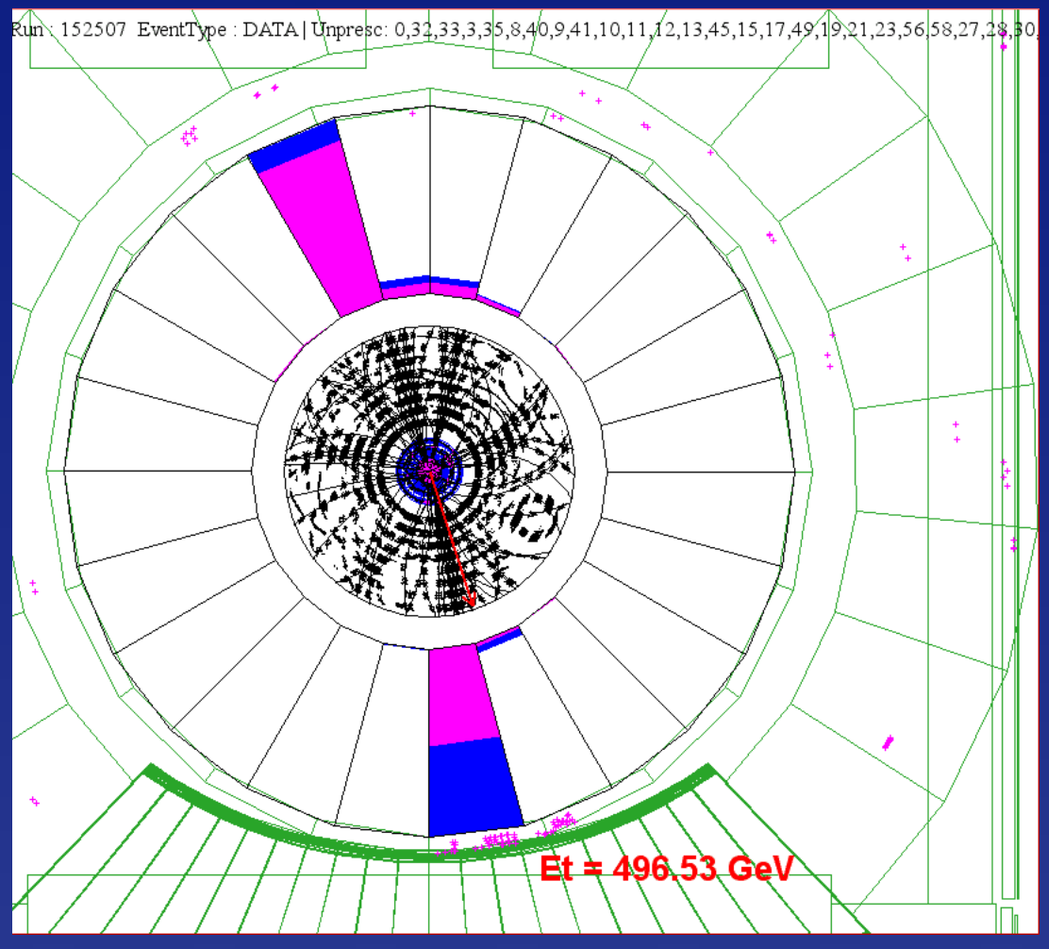
speed of protons in the LHC: c – 10 km/h

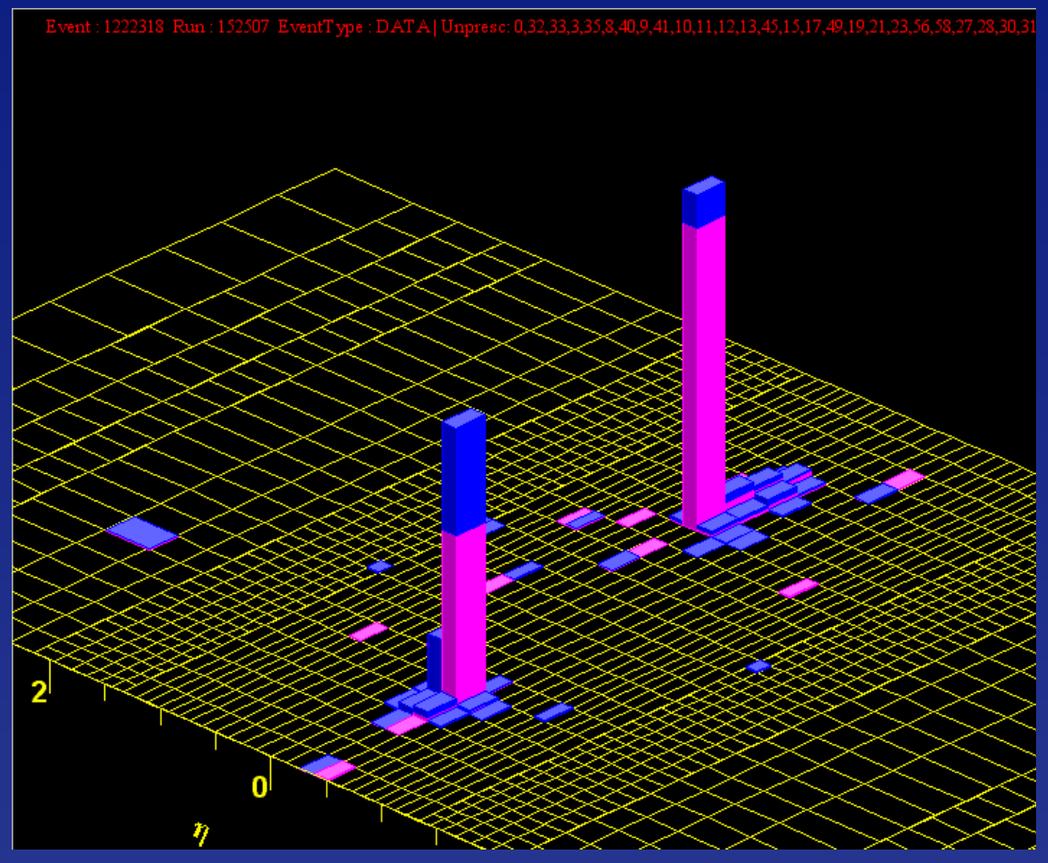
CDF Experiment



The World's Most Powerful Microscopes

nanonanophysics



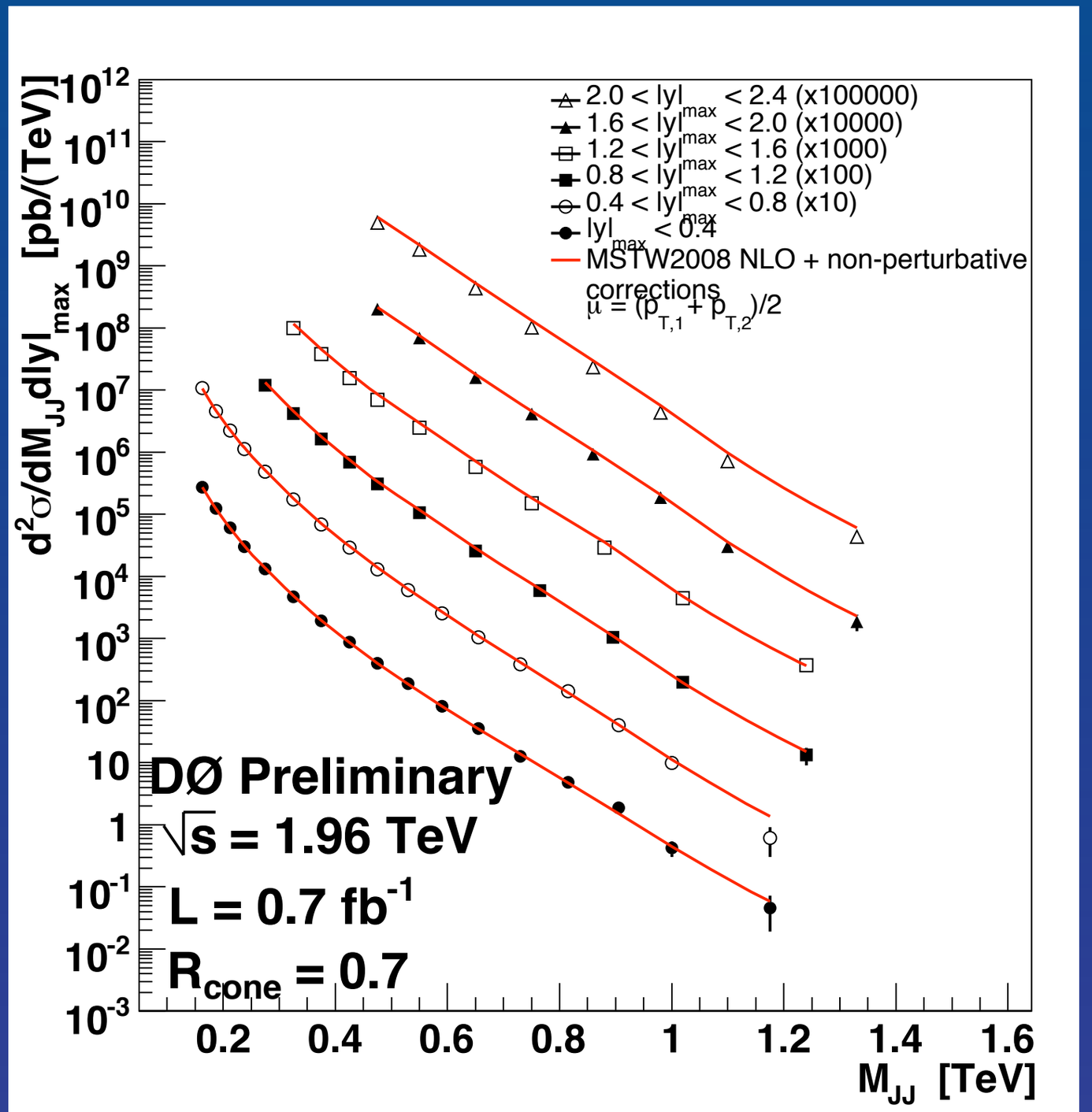


CDF two-jet event (70% of energy ⊥ beam direction)

quark + antiquark → jet + jet

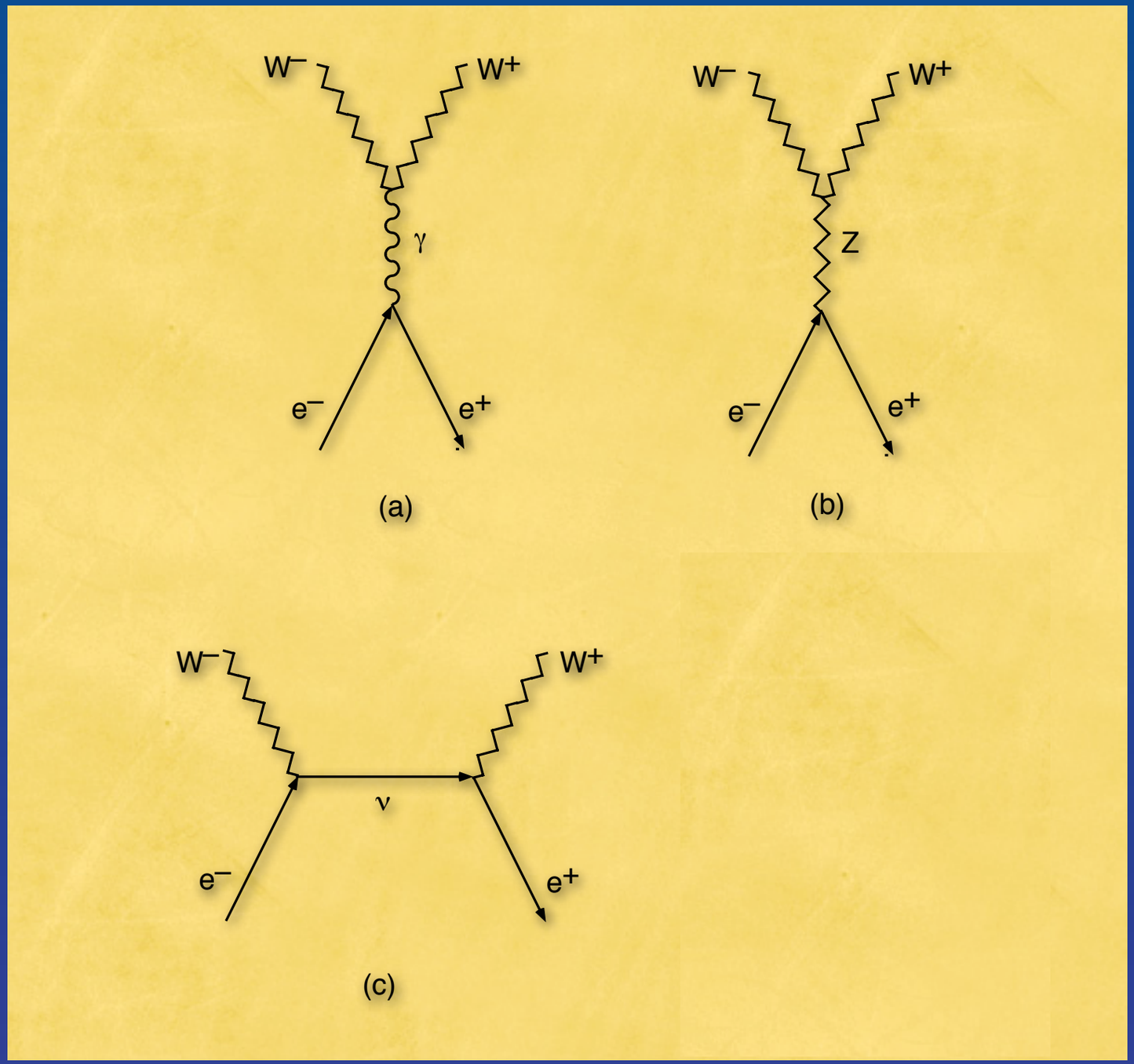
The World's Most Powerful Microscopes

nanonanophysics



Gauge symmetry (group-theory structure) tested in

$$e^+e^- \to W^+W^-$$



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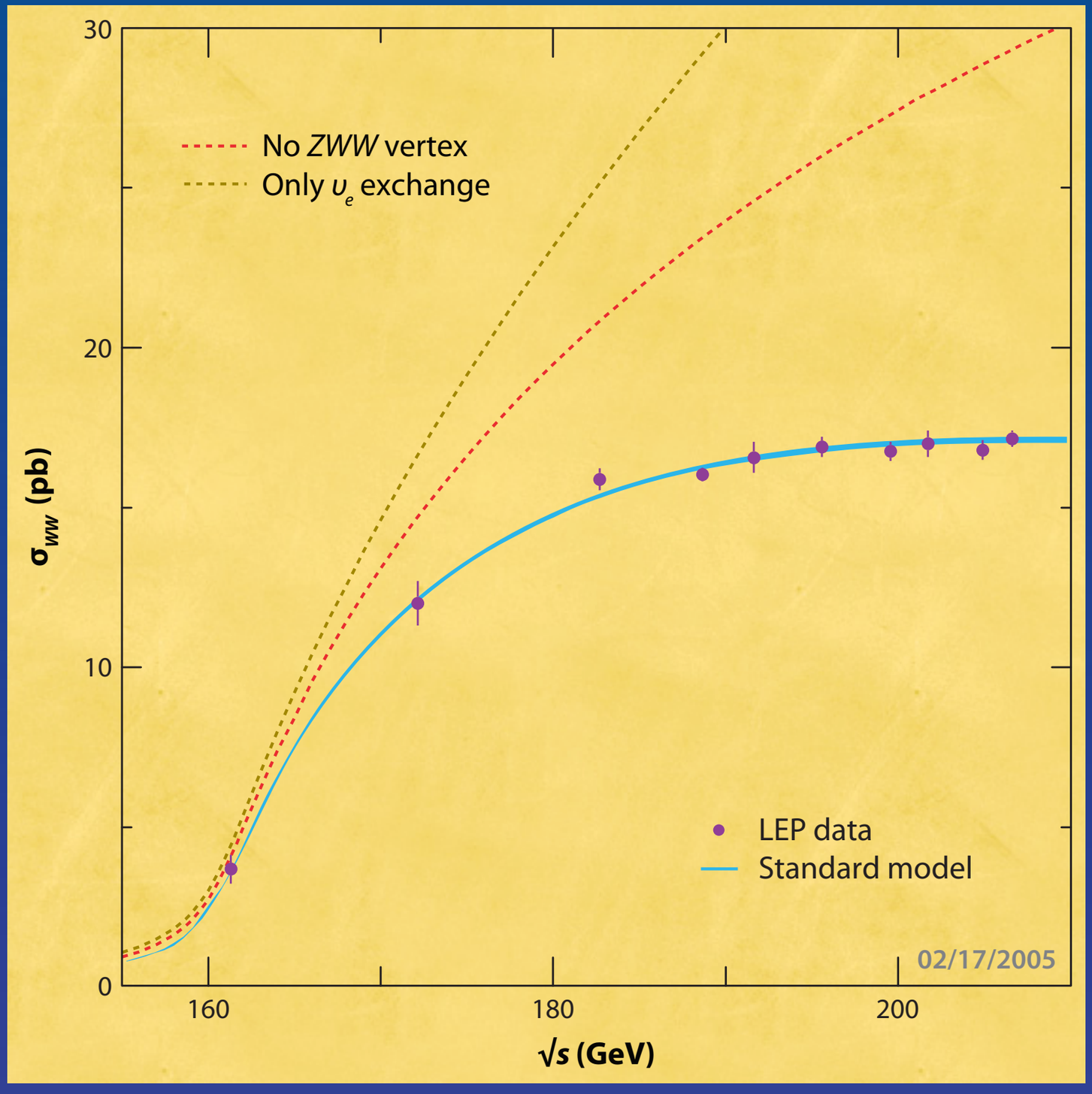

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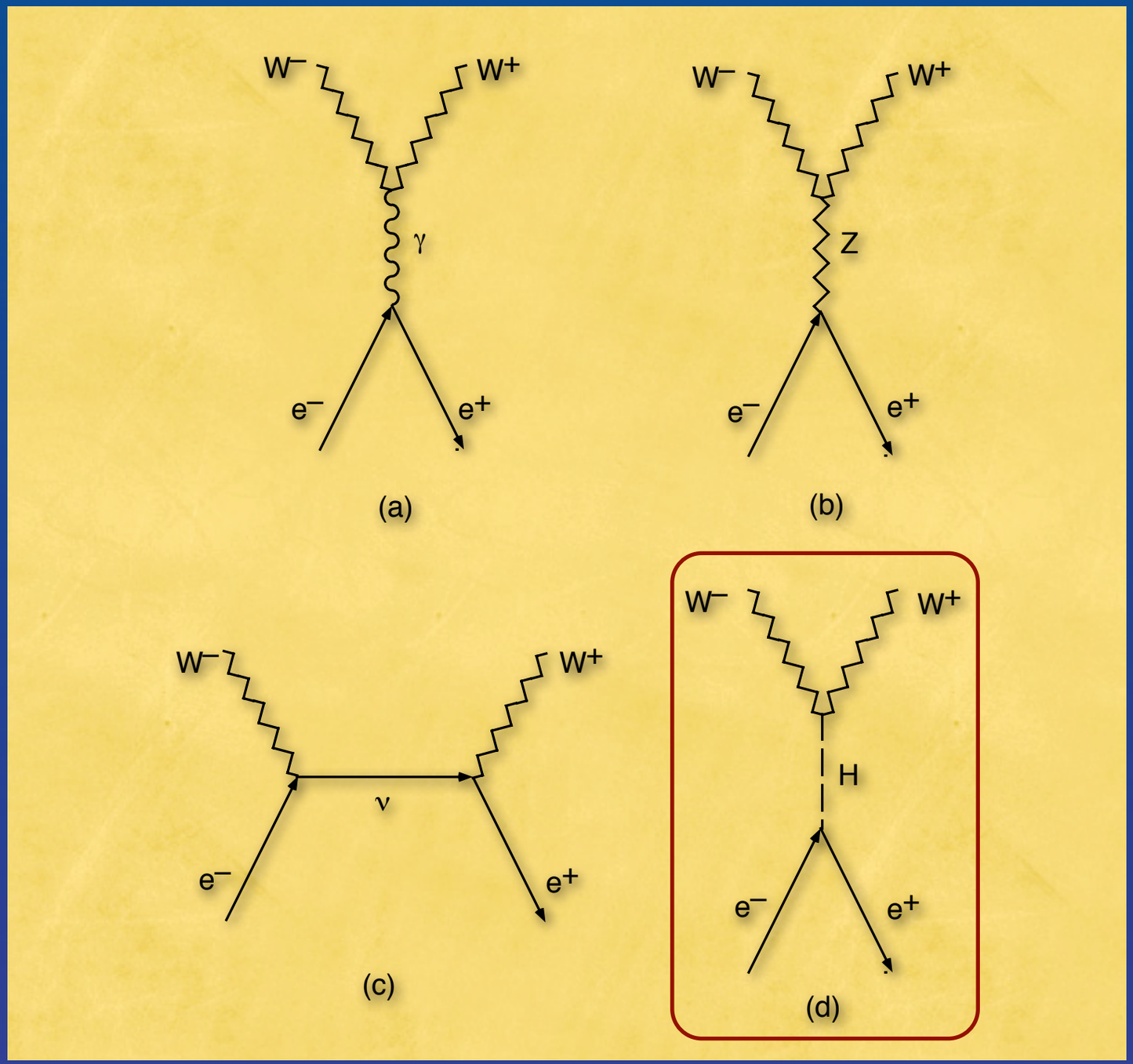
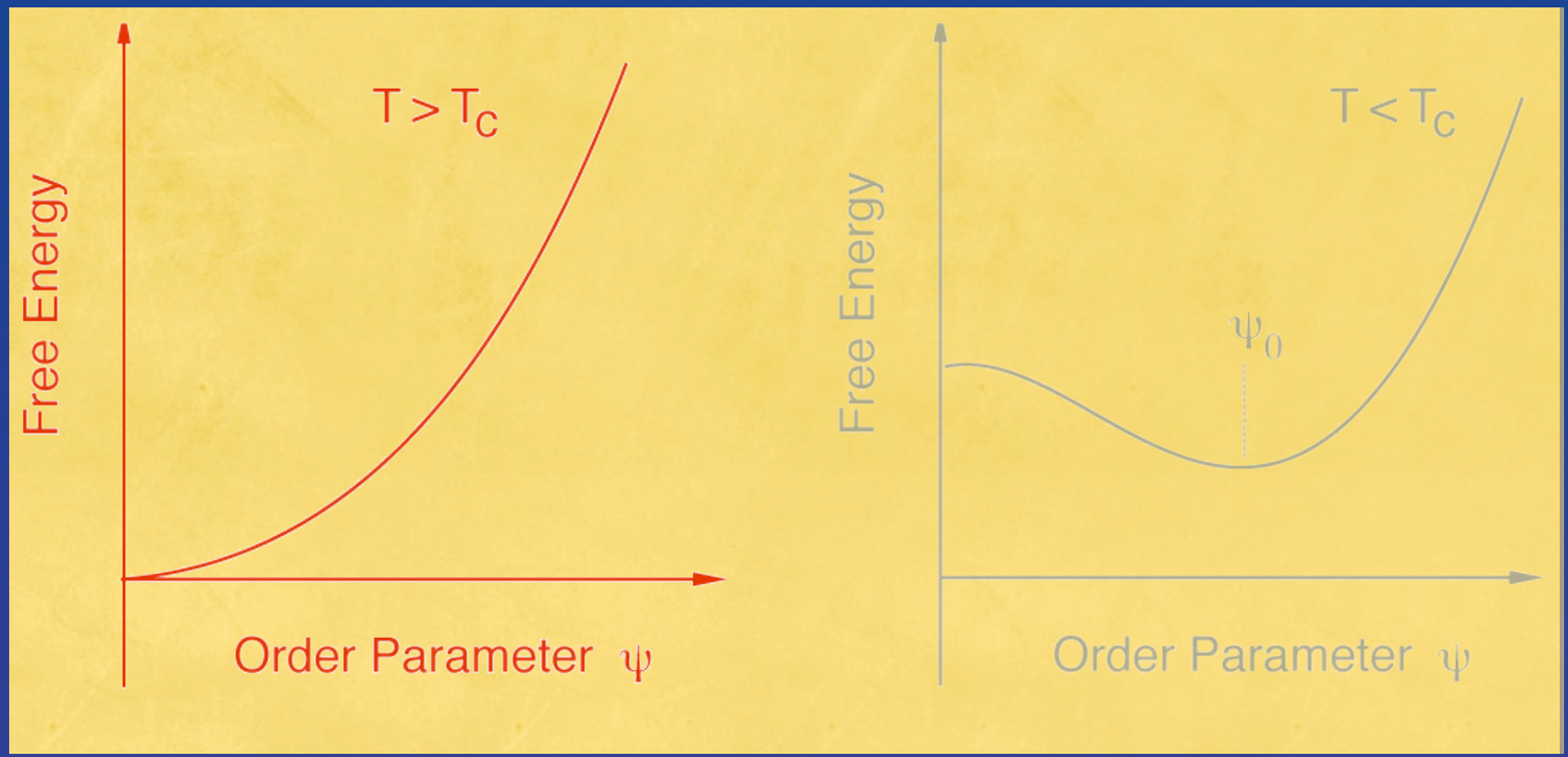


Massive weak bosons: Higgs boson

Meissner effect

The agent of electroweak symmetry breaking
represents a novel fundamental interaction
at an energy of a few hundred GeV …

We do not know the nature of the new force.



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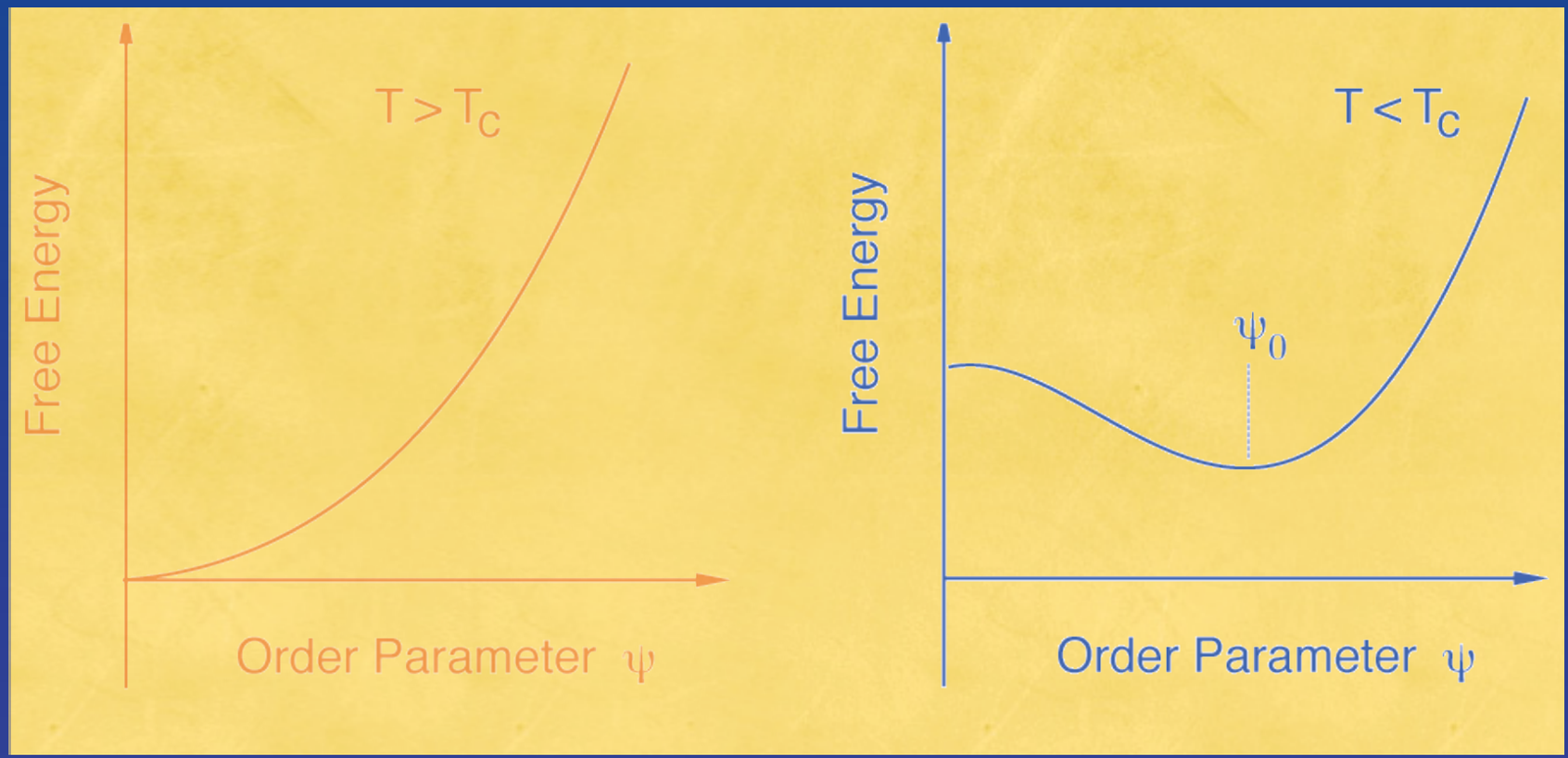


The Importance of the 1-TeV Scale

EW theory does not predict Higgs-boson mass

Thought experiment: *conditional upper bound*

W^+W^-, ZZ, HH, HZ satisfy s-wave unitarity,

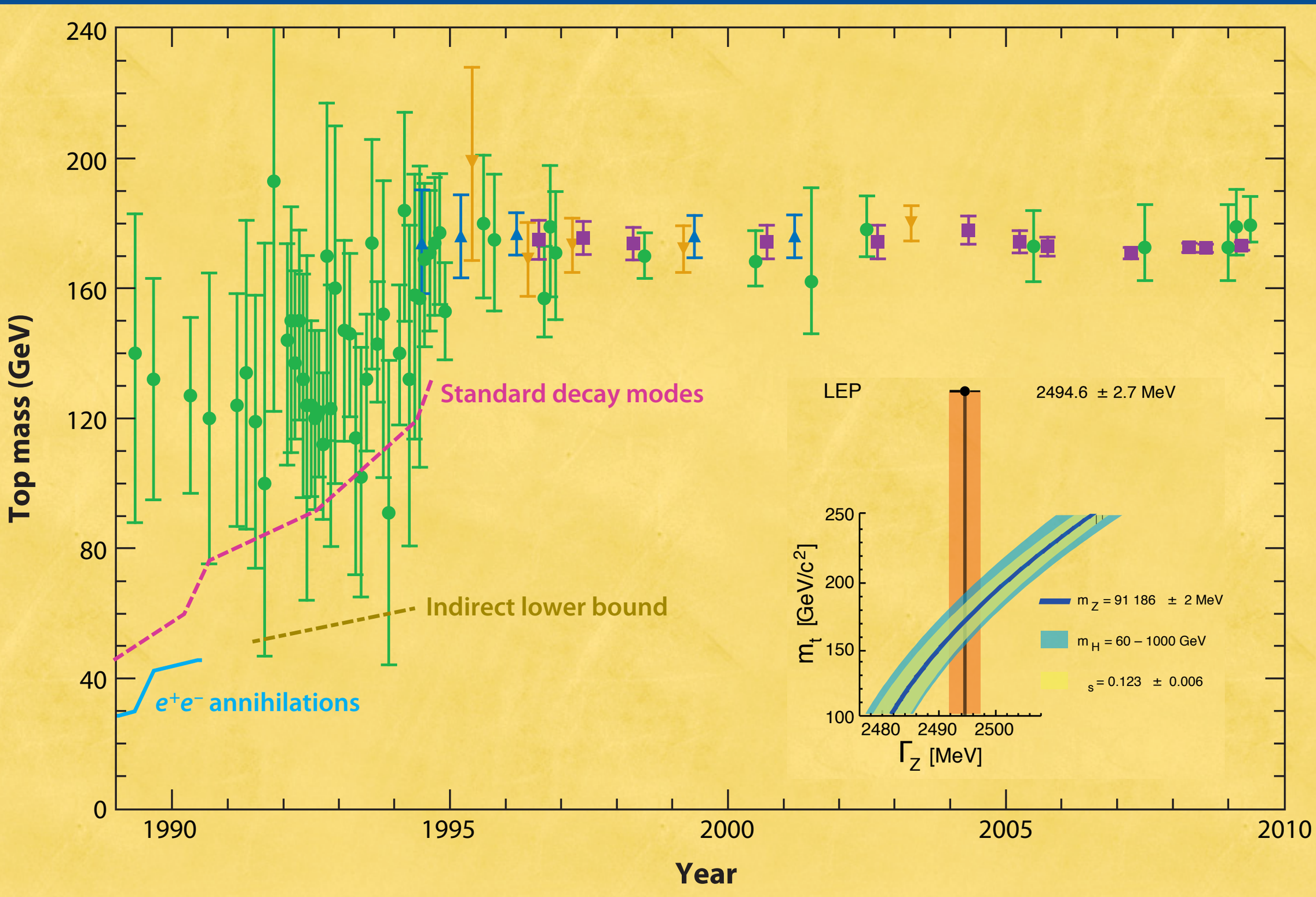
provided $M_H \leq (8\pi\sqrt{2}/3G_F)^{1/2} \approx 1$ TeV

- If bound is respected, perturbation theory is "everywhere" reliable
- If not, weak interactions among $W^{\pm}$, Z, H become strong on 1-TeV scale

New phenomena are to be found around 1 TeV

Precision Measurements Test the Theory …

… and determine unknown parameters



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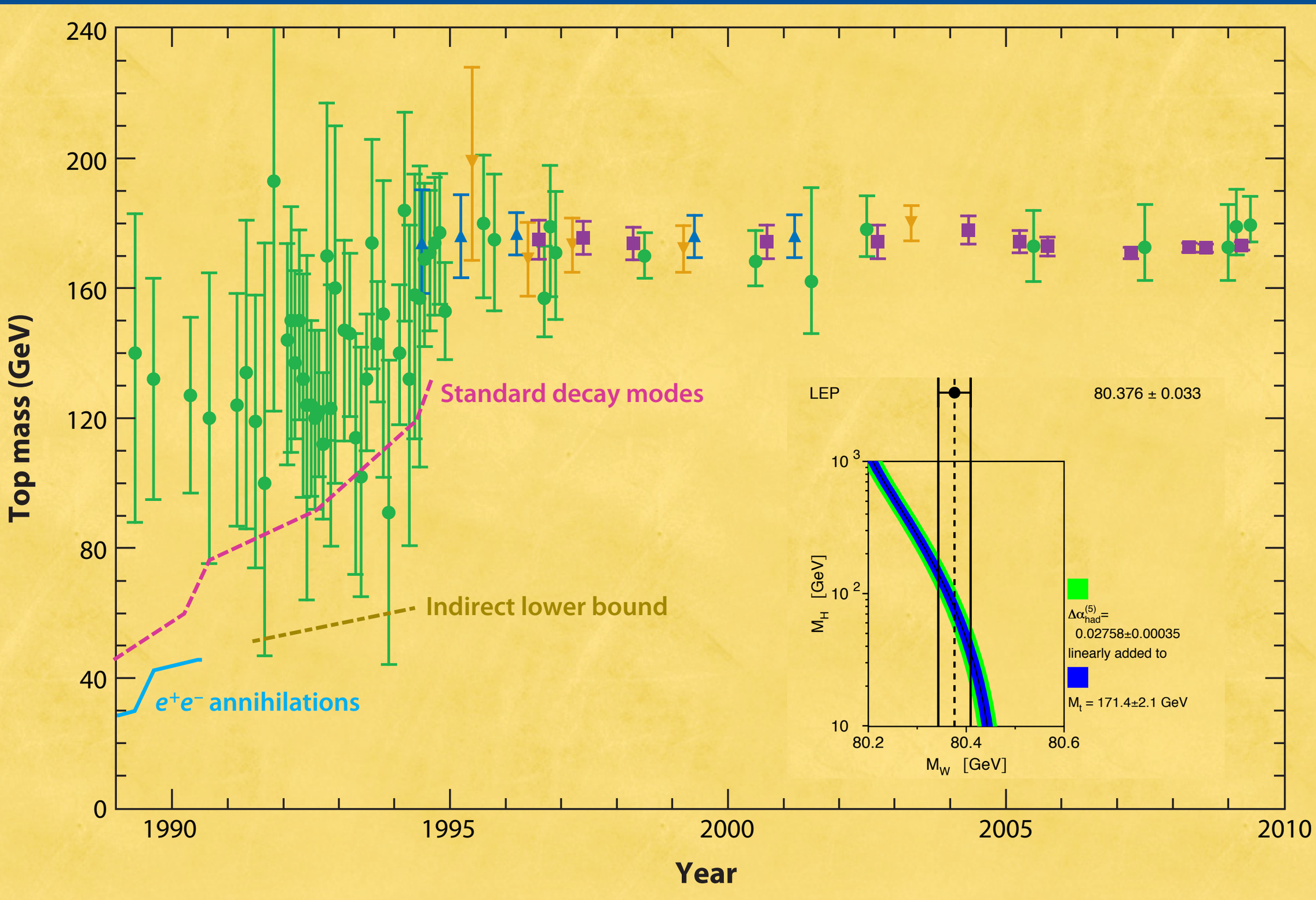
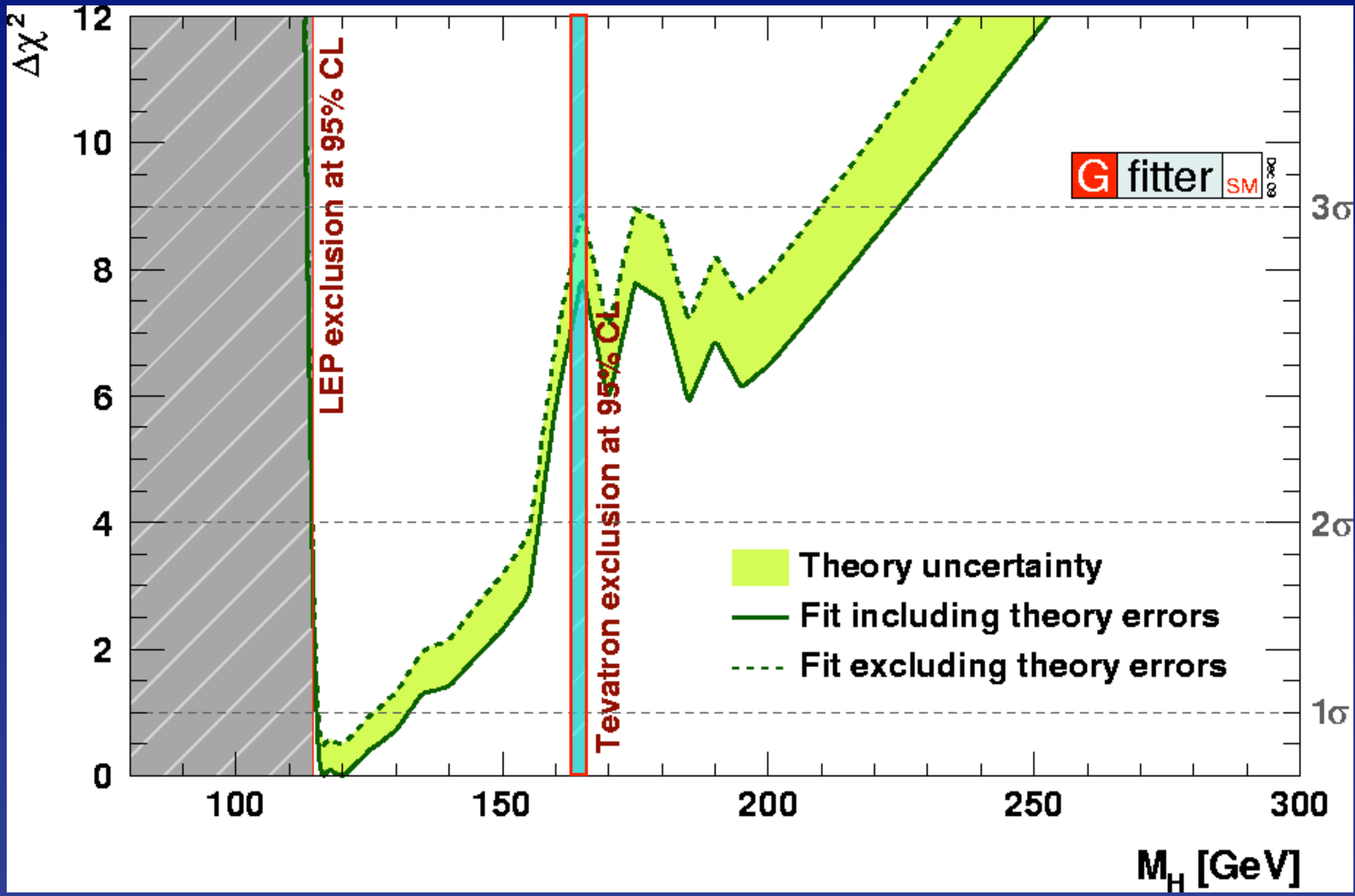


Where the (standard) Higgs boson might be



What is the nature of the mysterious new force that hides electroweak symmetry?

- A force of a new character, based on interactions of an elementary scalar
- A new gauge force, perhaps acting on undiscovered constituents
- A residual force that emerges from strong dynamics among electroweak gauge bosons
- An echo of extra spacetime dimensions

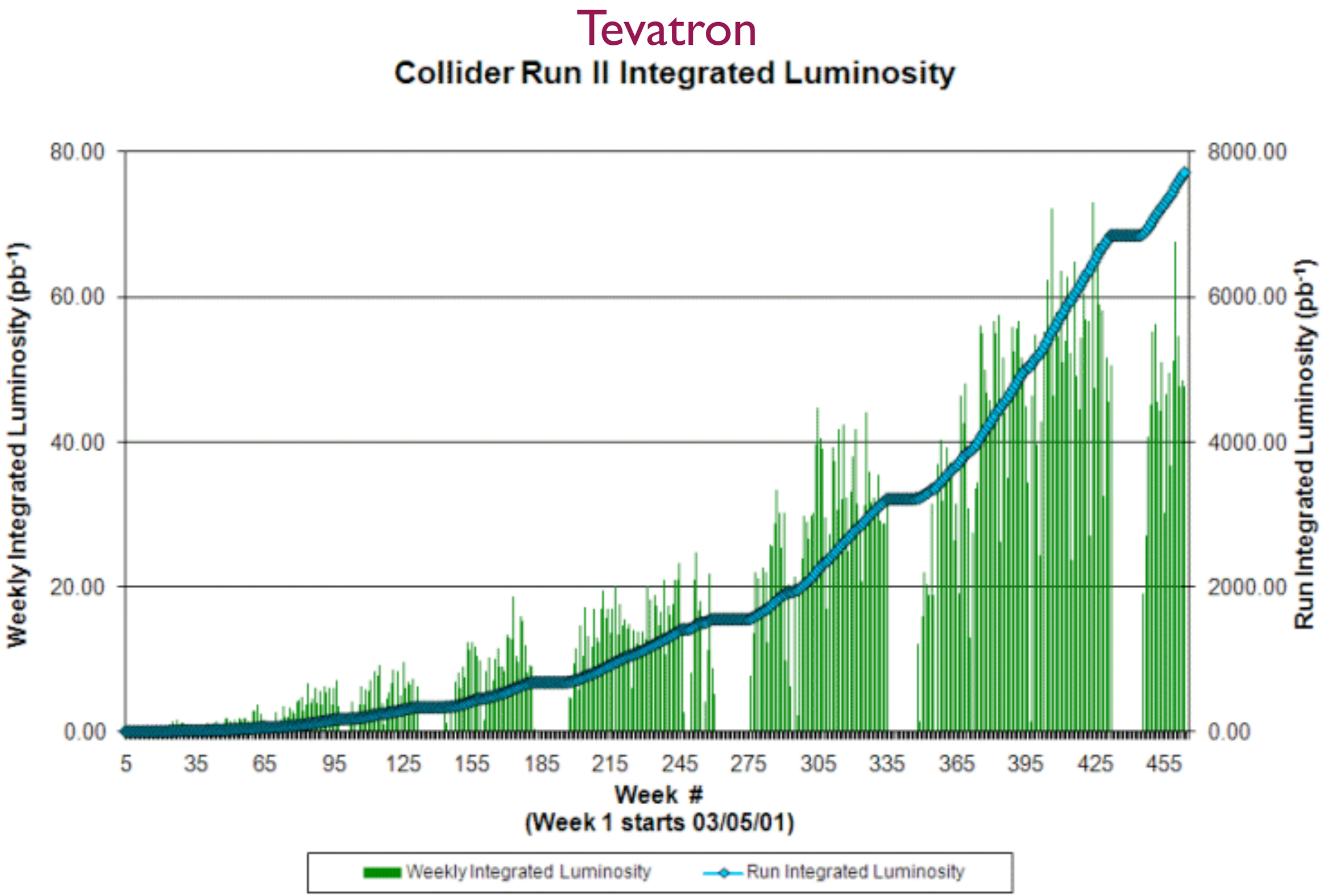
Which path has Nature taken?

Essential step toward understanding the new force that shapes our world:
Find the Higgs boson and explore its properties.

- ✳ Is it there? How many?
- ✳ Verify quantum numbers (spin, parity, …)
- ✳ Does *H* generate mass for gauge bosons and for fermions?
- ✳ How does *H* interact with itself?

Finding the Higgs boson starts a new adventure!

Tevatron


Collider Run II Integrated Luminosity
80.00
60.00
40.00
20.00
0.00
8000.00
6000.00
4000.00
2000.00
0.00
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
5
35
65
95
125
155
185
215
245
275
305
335
365
395
425
455
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

Large Hadron Collider · CERN

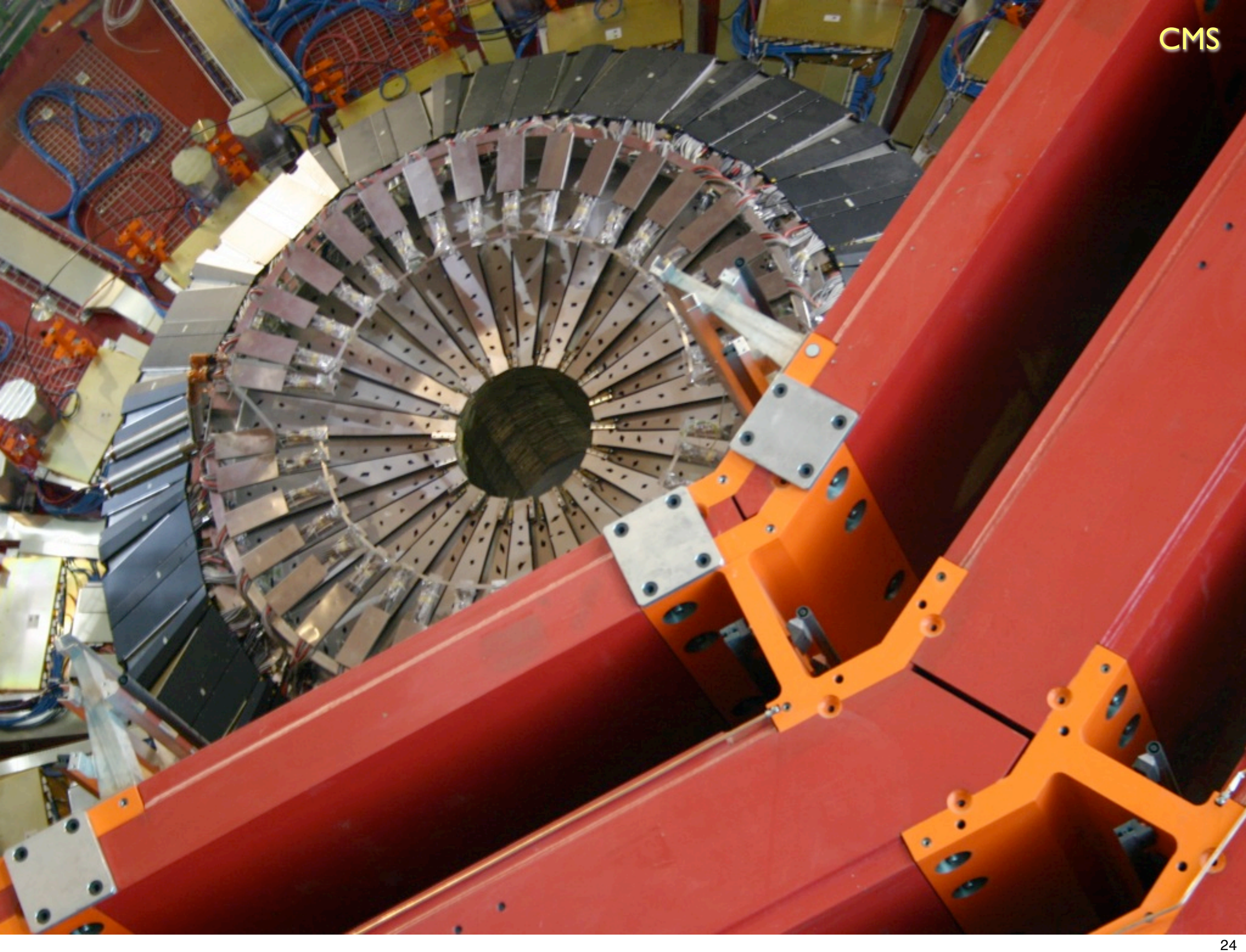
proton-proton collisions at 7 TeV/beam

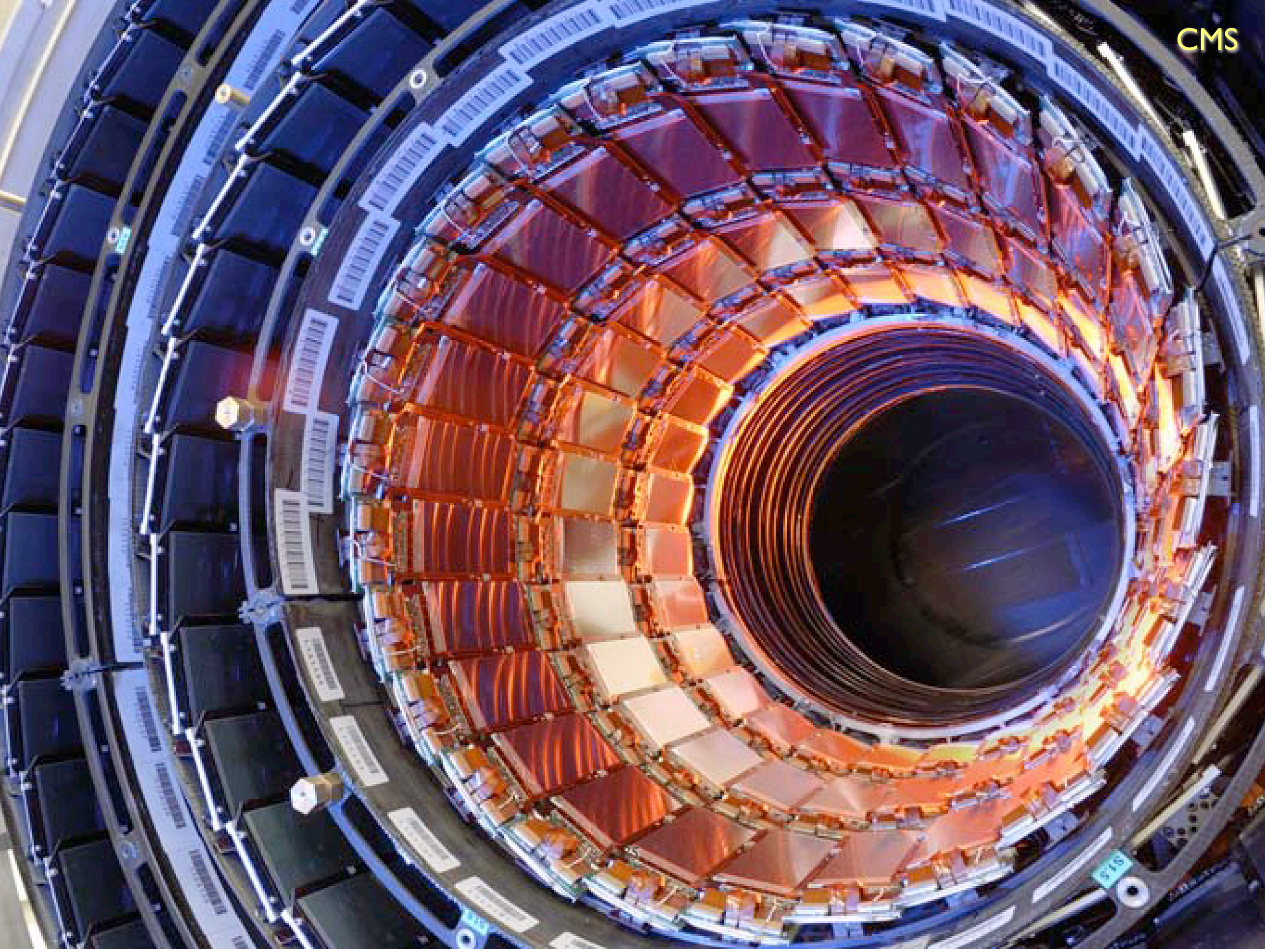
CMS

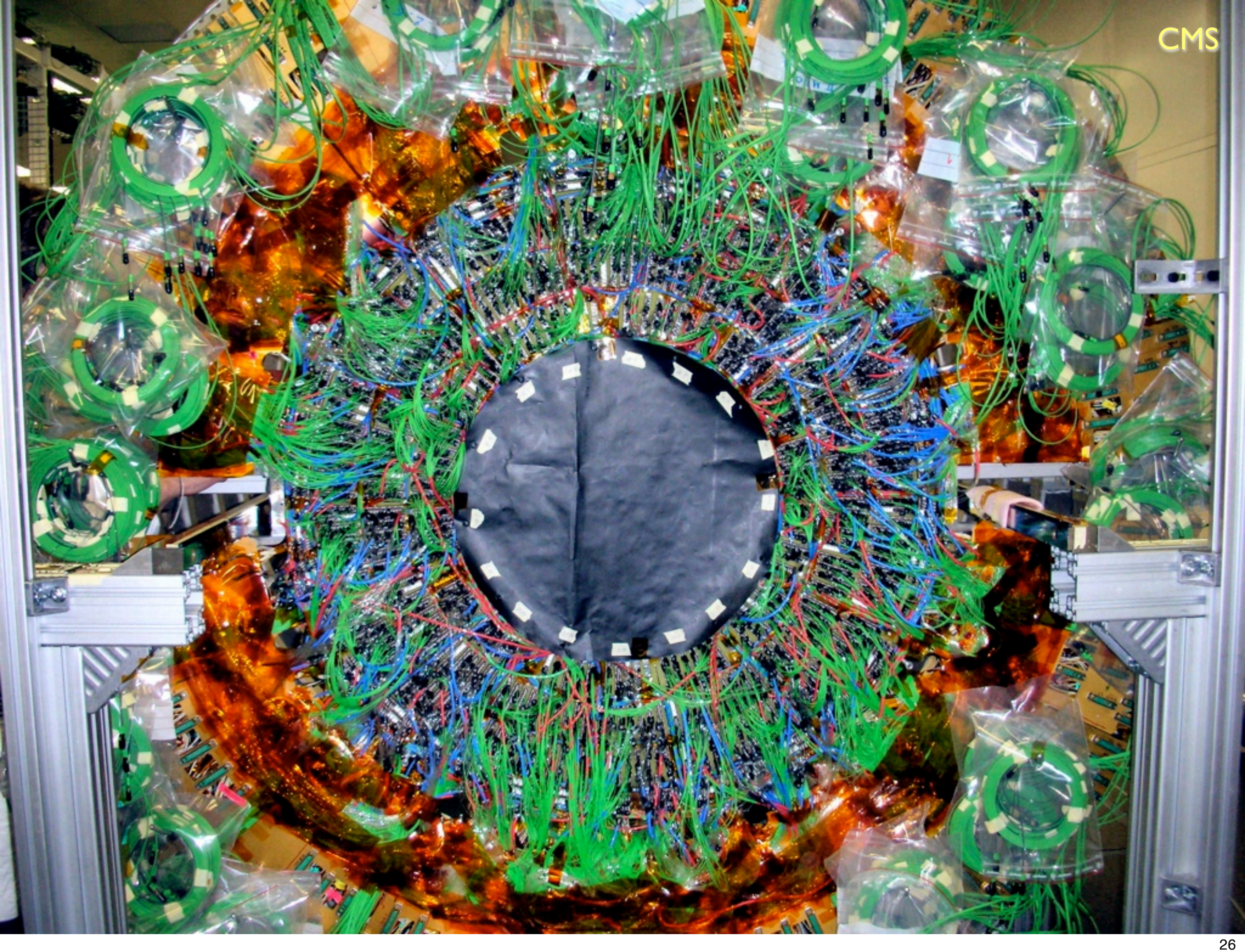
LHCb

ALICE

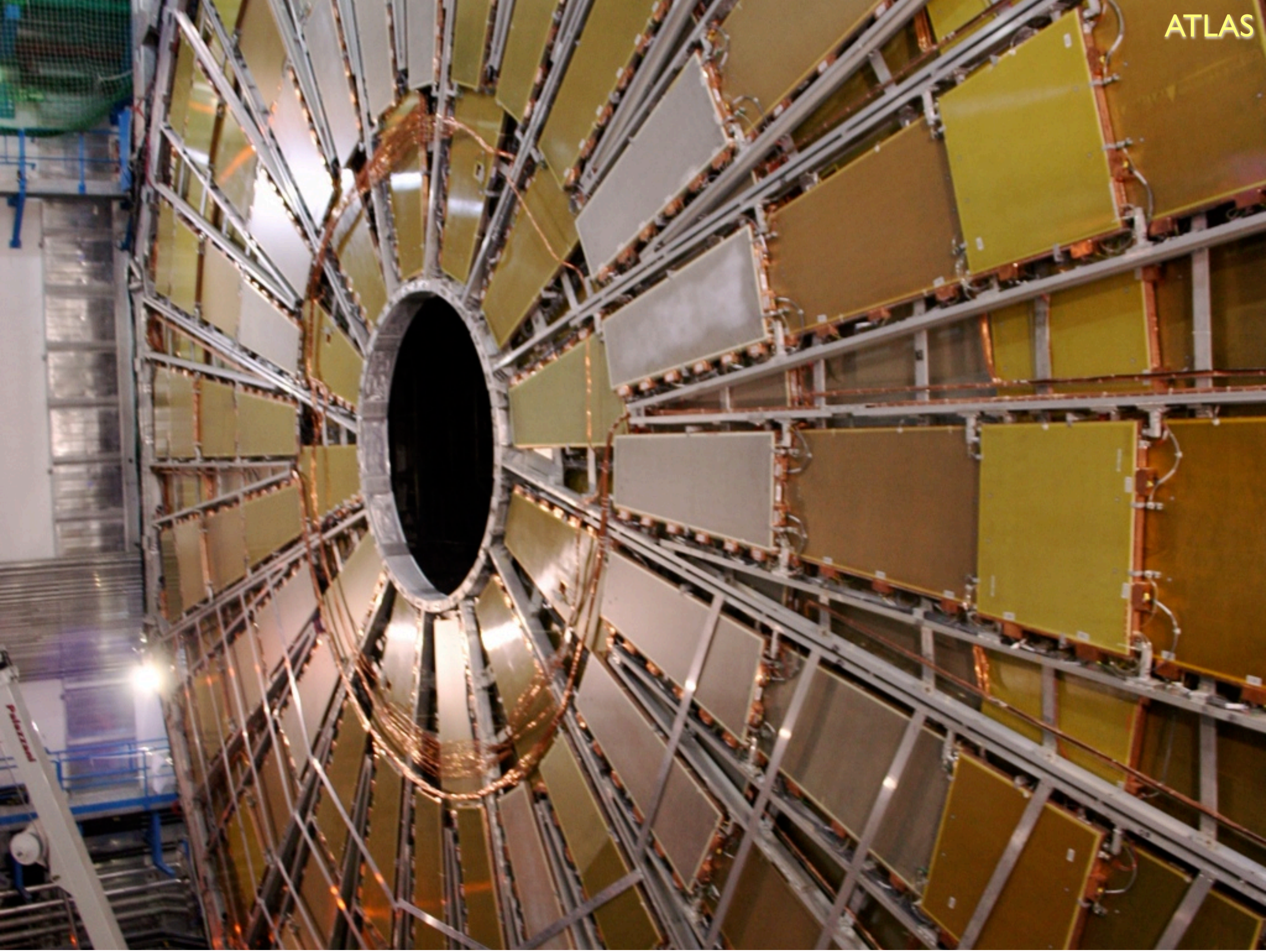
ATLAS

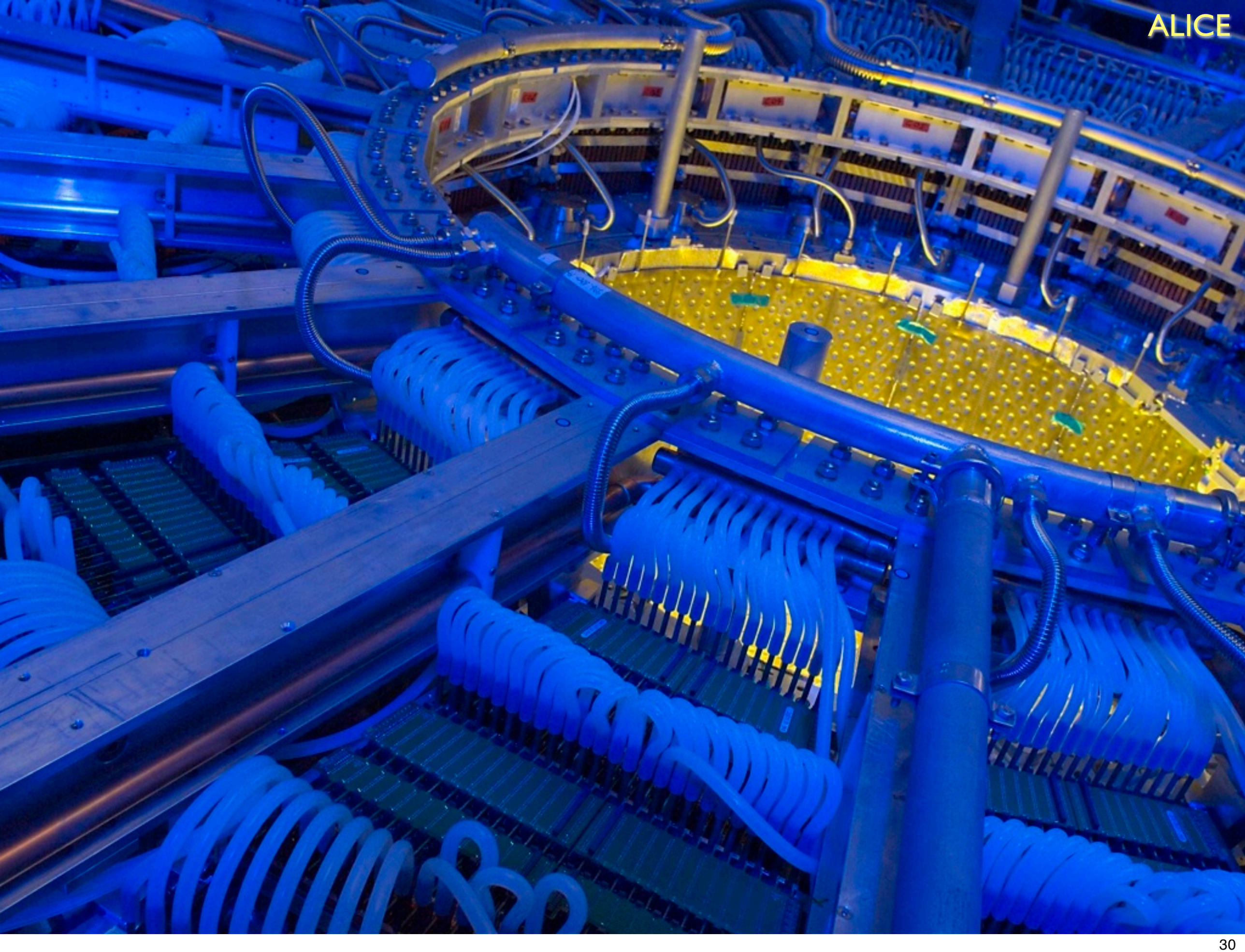

CMS


CMS


CMS

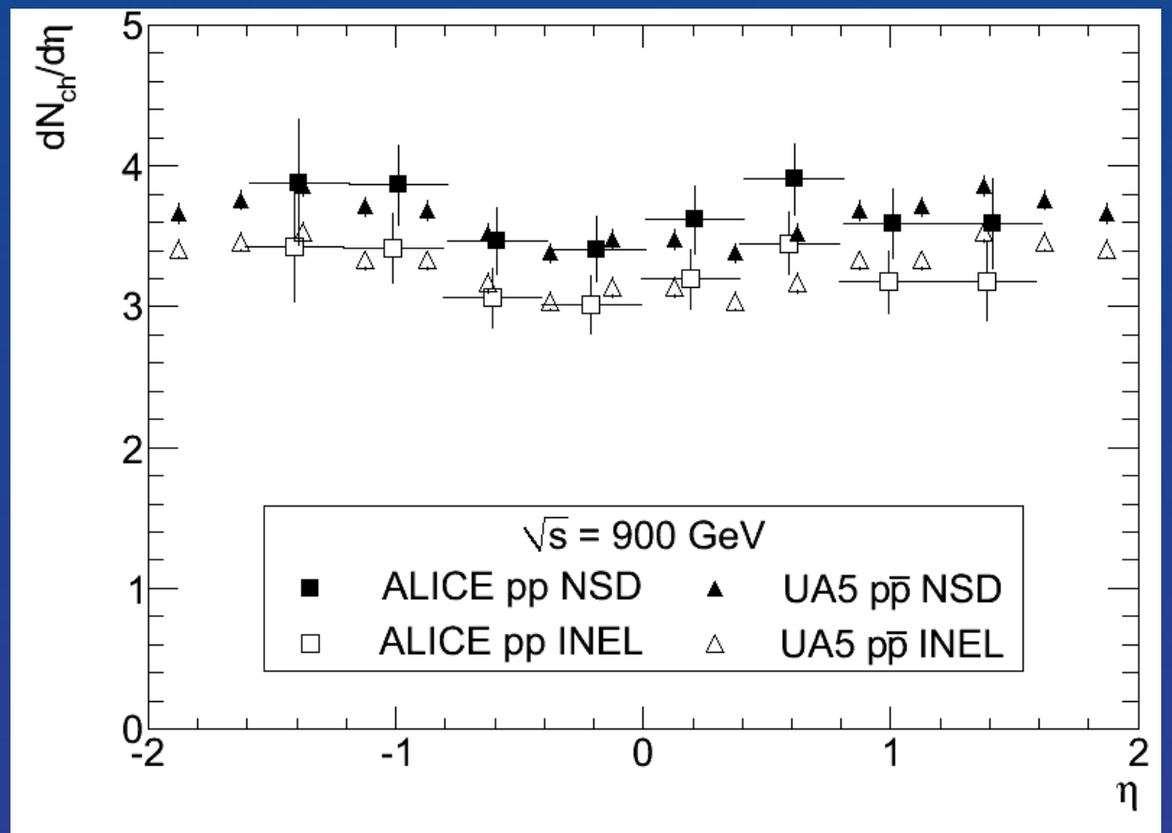
ATLAS

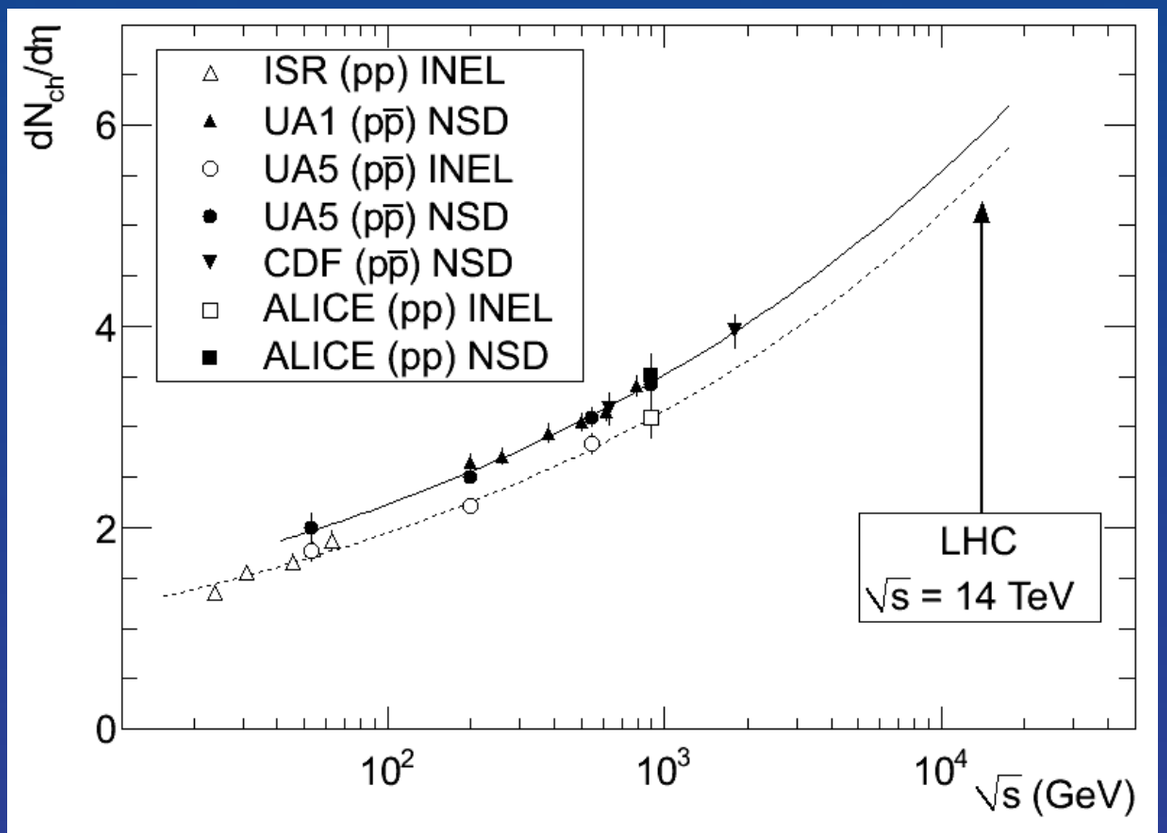




First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the charged-particle pseudorapidity density at $\sqrt{s} = 900\,\text{GeV}$

ALICE collaboration






LHCb

Why will it matter?

Understanding the everyday …

Why atoms?

Why chemistry?

Why stable structures?

Imagine a world without a Higgs mechanism

Without a Higgs mechanism …

Electron and quarks would have no mass

QCD would confine quarks into protons, etc.

Nucleon mass little changed

Surprise: QCD would hide EW symmetry,

give tiny masses to W, Z

Massless electron: atoms lose integrity

No atoms means no chemistry, no stable composite structures like liquids, solids, …

… character of the physical world would be profoundly changed

arXiv:0901.3958

Revolution:

The Meaning of Identity

Varieties of matter

- ▷ What sets masses and mixings of quarks and leptons?
- ▷ What is $\mathcal{CP}$ violation trying to tell us?
- ▷ Neutrino oscillations give us another take, might hold a key to the matter excess in the Universe.

All fermion masses and mixings mean new physics

- ▷ Will new kinds of matter help us to see the pattern?

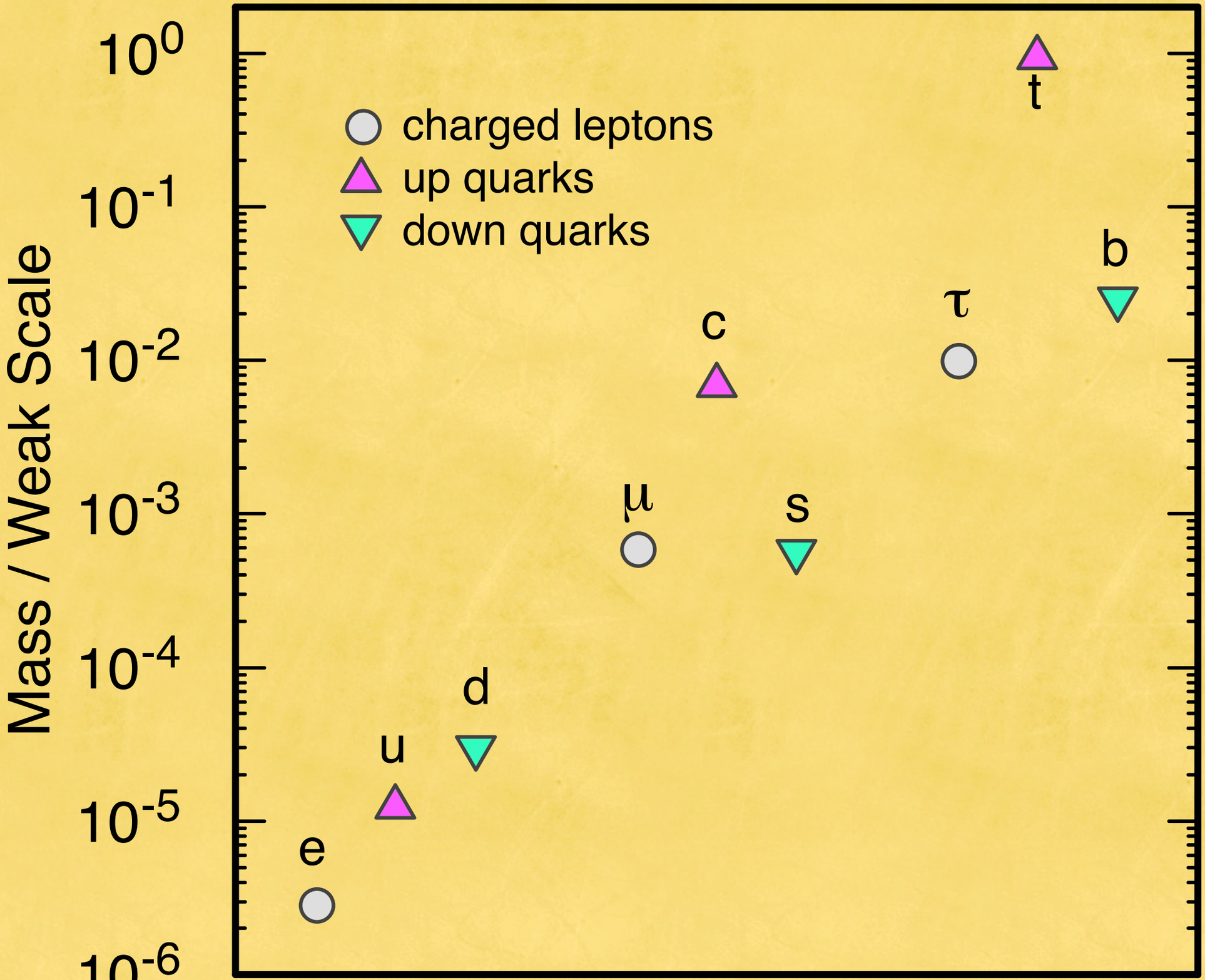
What makes a top quark a top quark,
an electron an electron, a neutrino a neutrino?

Parameters of the Standard Model

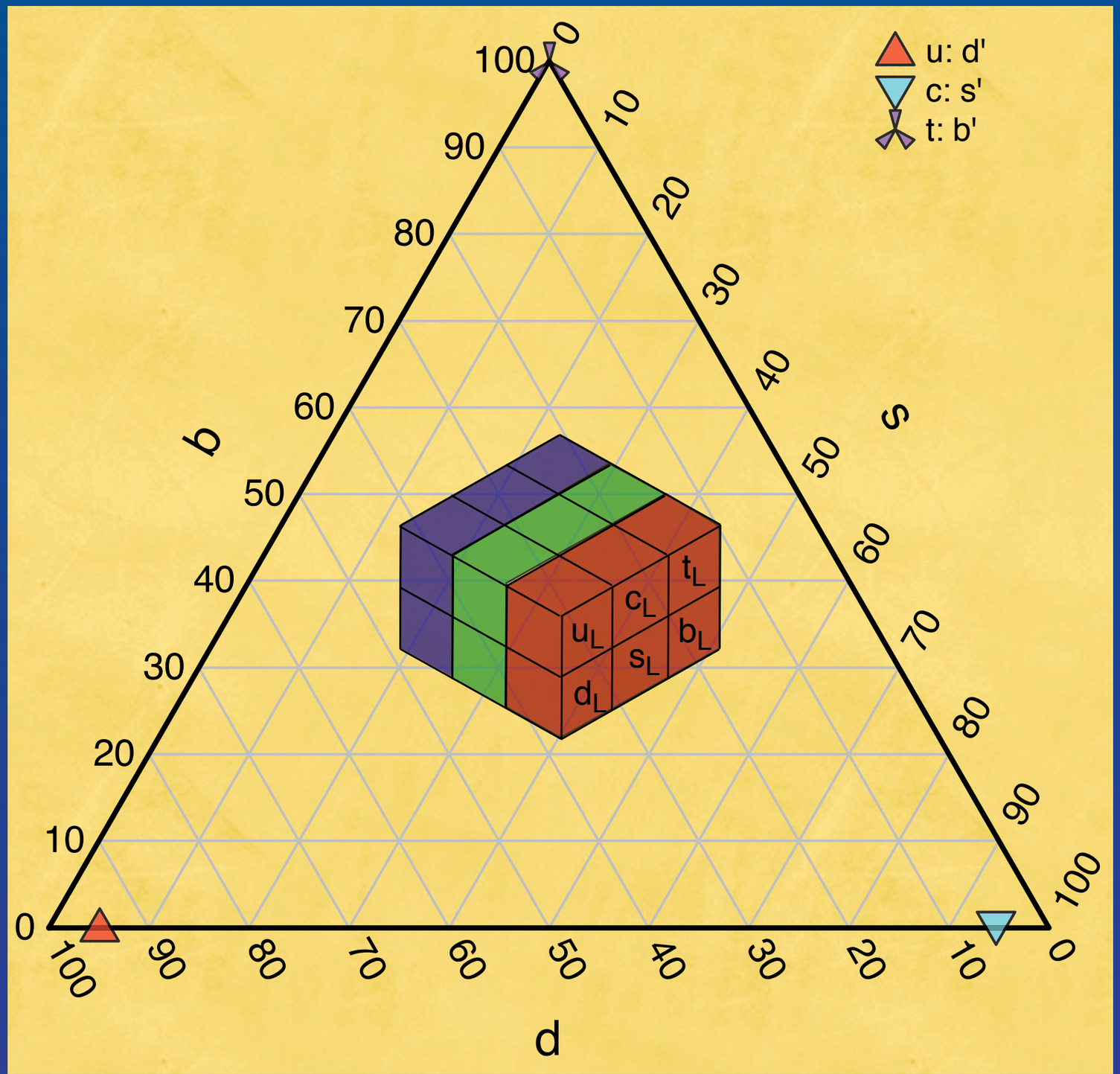
3	coupling parameters $\alpha_s, \alpha_{\mathsf{em}}, \sin^2\theta_W$
2	parameters of the Higgs potential
1	vacuum phase (QCD)
6	quark masses
3	quark mixing angles
1	CP-violating phase
3	charged-lepton masses
3	neutrino masses
3	leptonic mixing angles
1	leptonic CP-violating phase (+ Majorana . . .)
26^+	arbitrary parameters

Flavor physics may be where we see, or diagnose, the break in the SM.

$\supset$

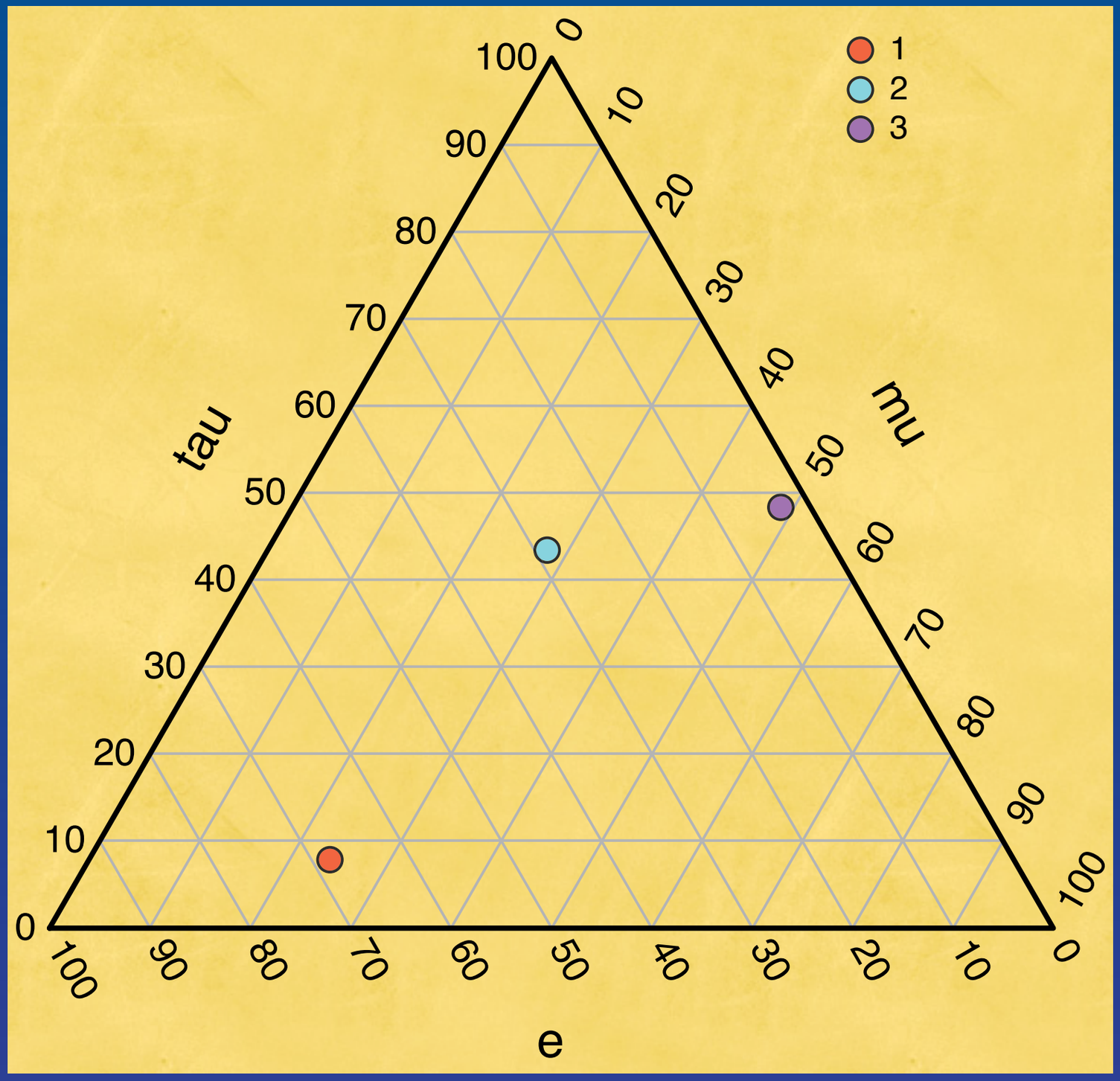

charged leptons
up quarks
down quarks
Mass / Weak Scale
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
t
b
τ
c
μ
s
d
u
e

Quark family patterns: *generations*

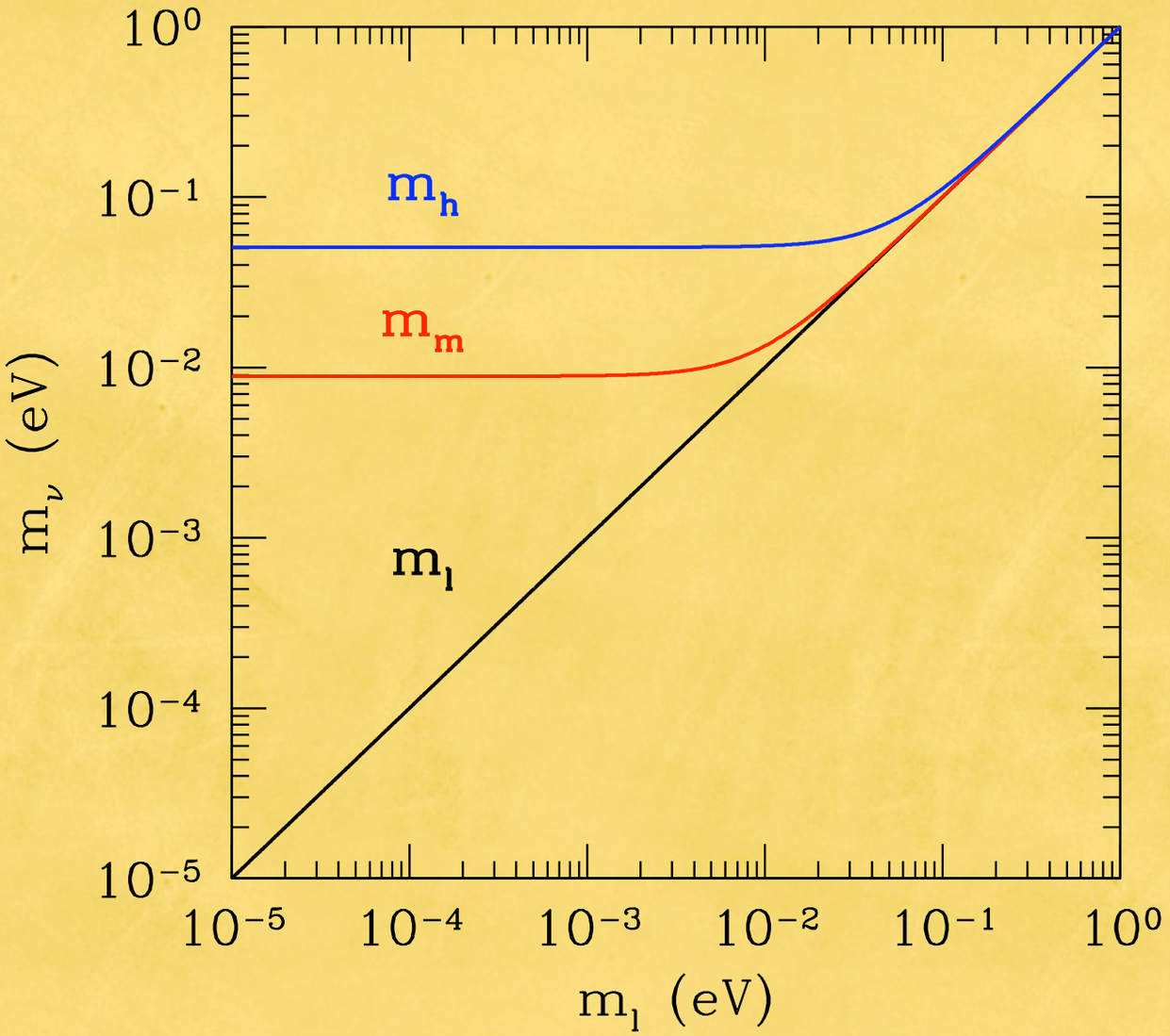


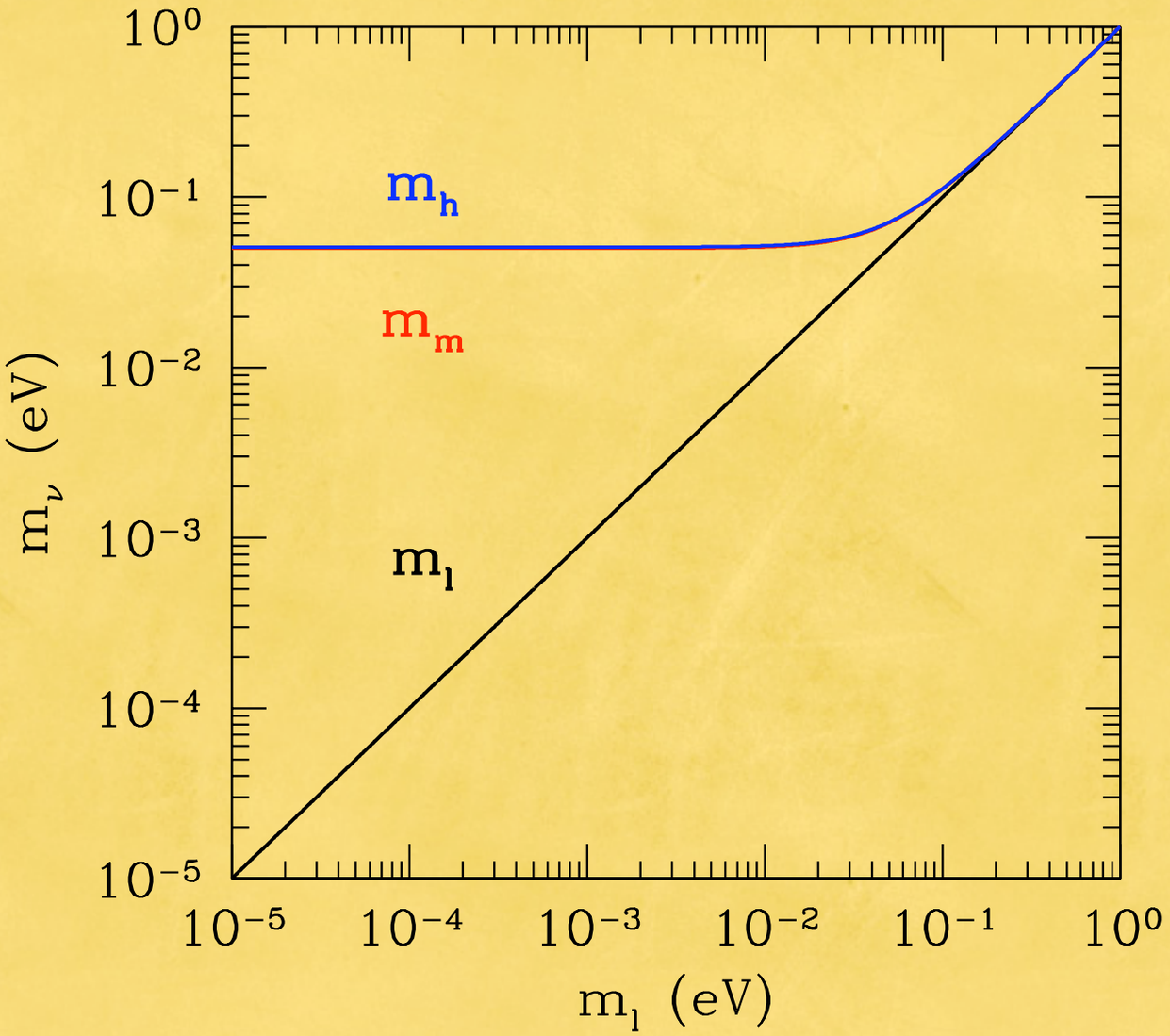
Veltman: Higgs boson knows something we don't know!

Neutrino family patterns (an example)



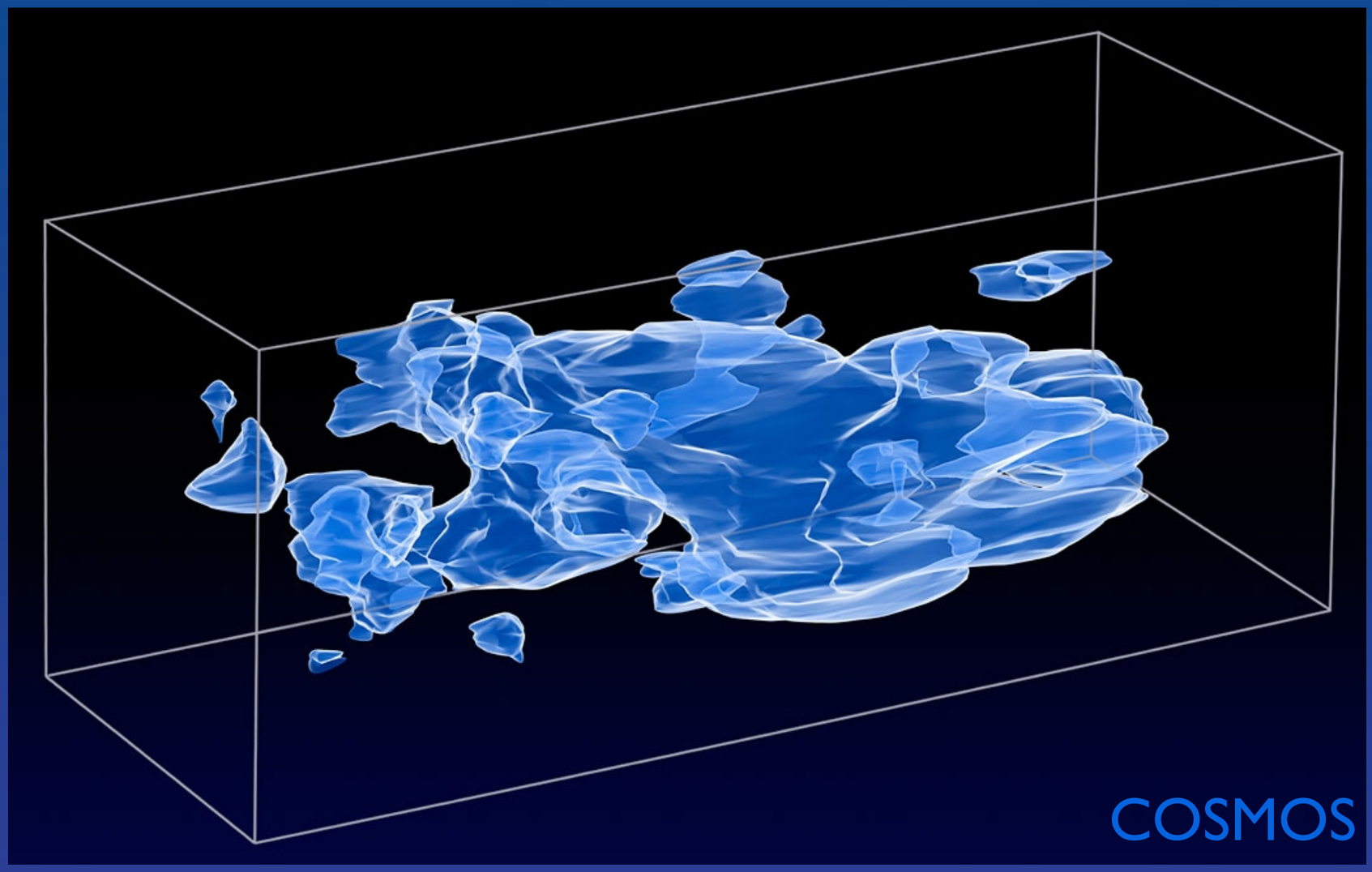
Neutrino Masses



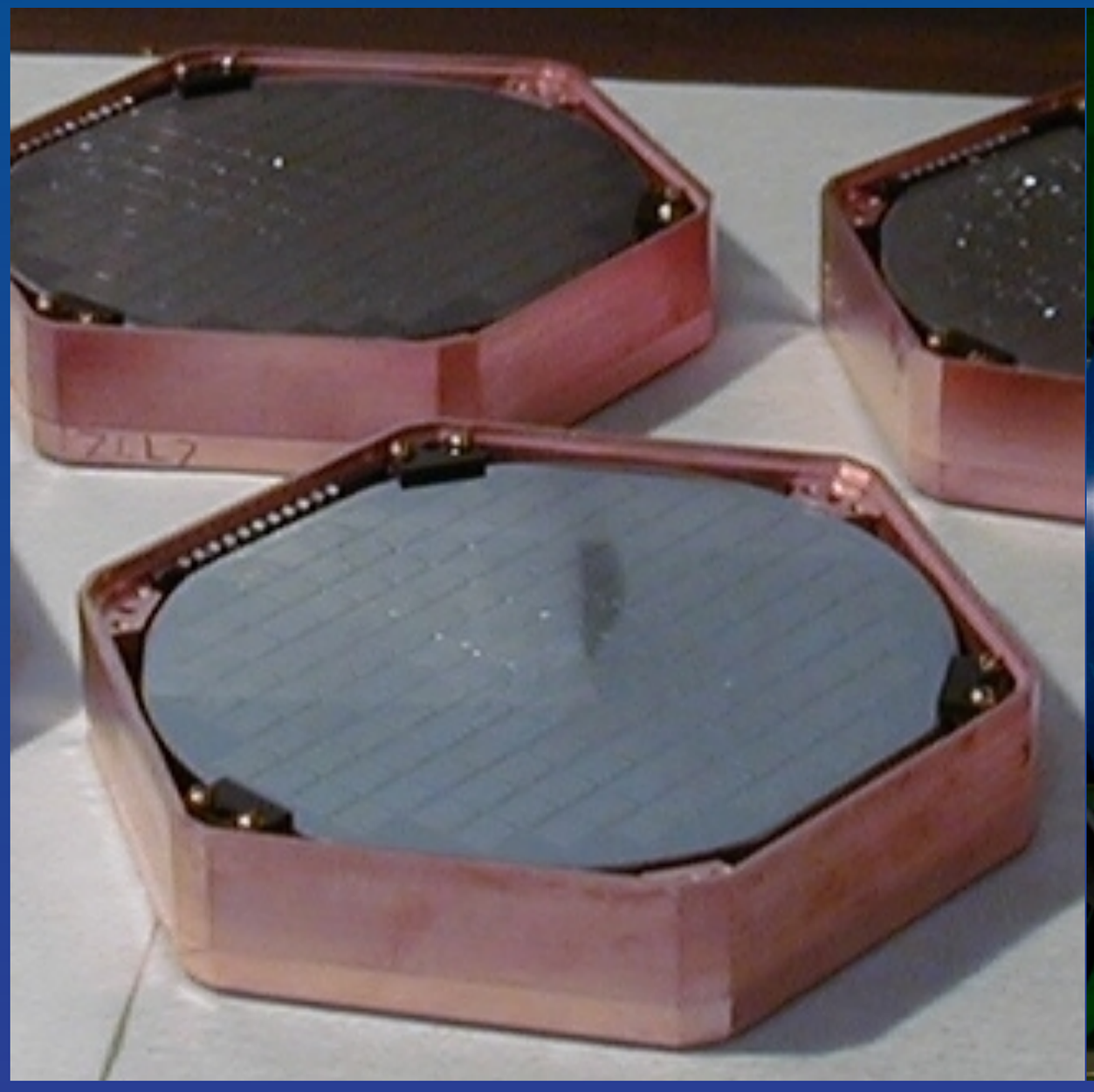


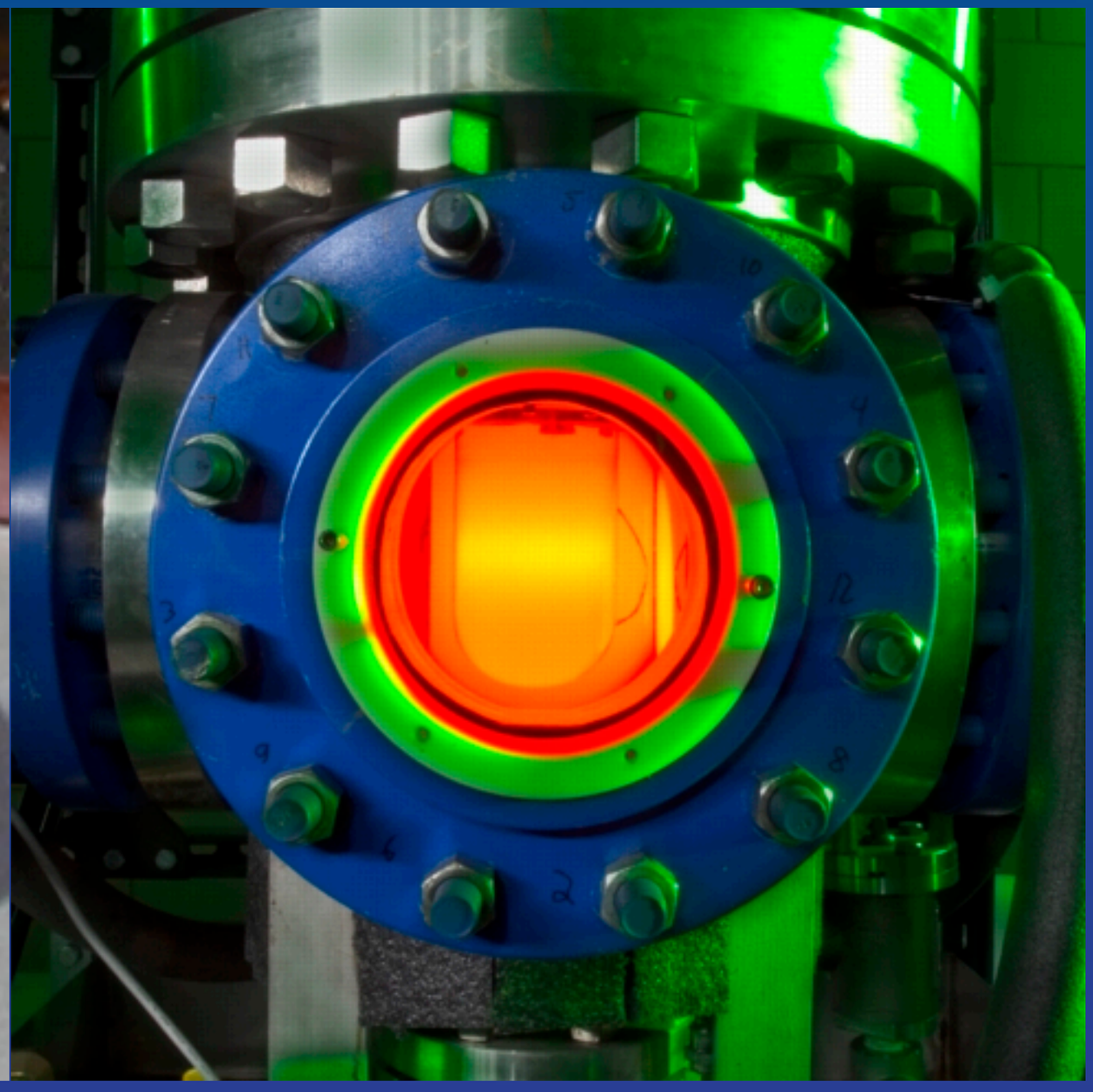
More New Physics on the Fermi Scale?

If dark matter interacts weakly …



… its likely mass is 0.1 to 1 TeV: *Fermi scale*





Many extensions to EW theory entail dark matter candidates

Supersymmetry is highly developed, has several important consequences:

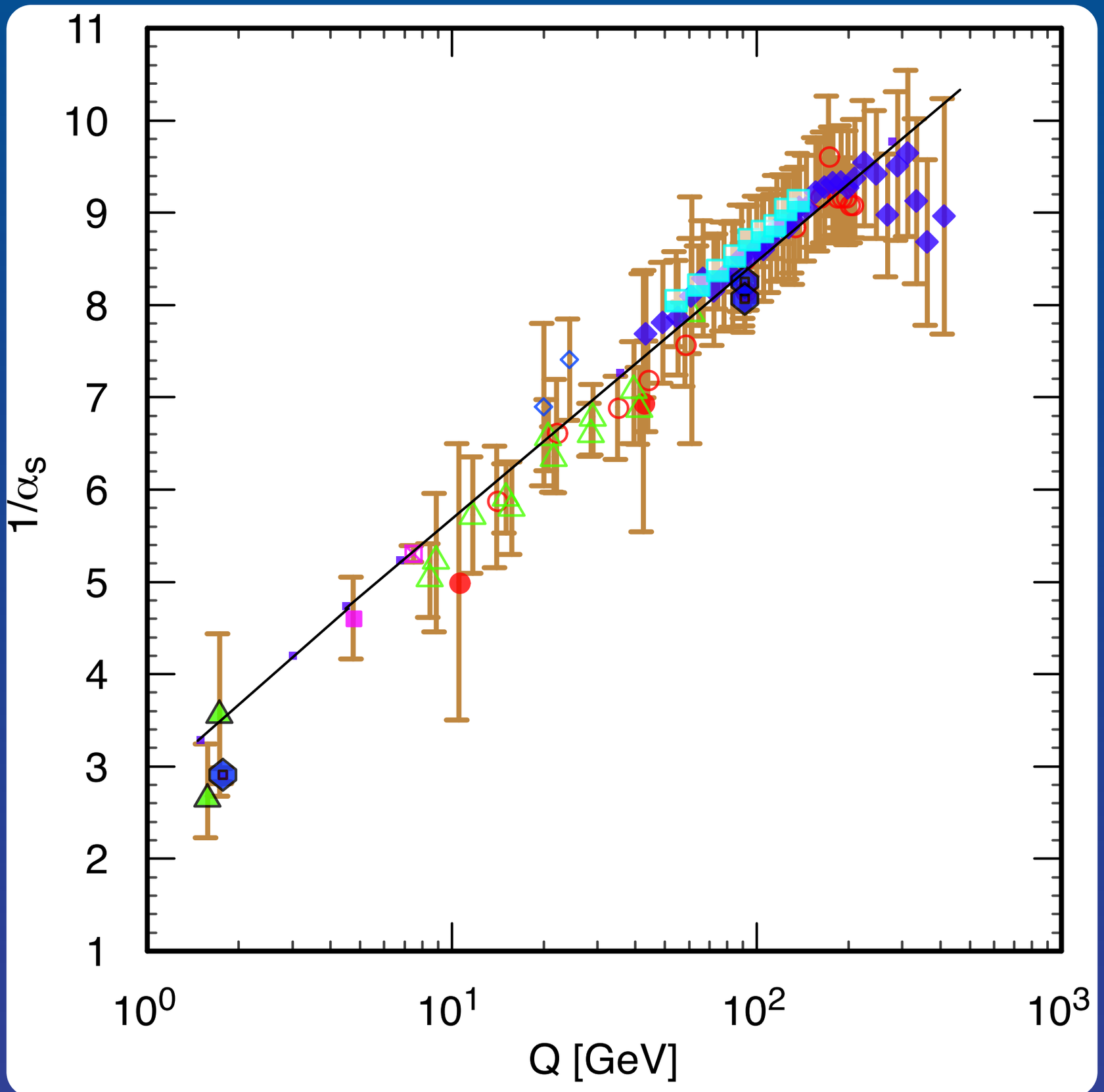
- ✳Predicts that Higgs field condenses, breaking EW symmetry, if top is heavy
- ✳Predicts a light Higgs mass
- ✳Implies cosmological cold dark matter
- ✳In a unified theory, explains the values of standard-model coupling constants

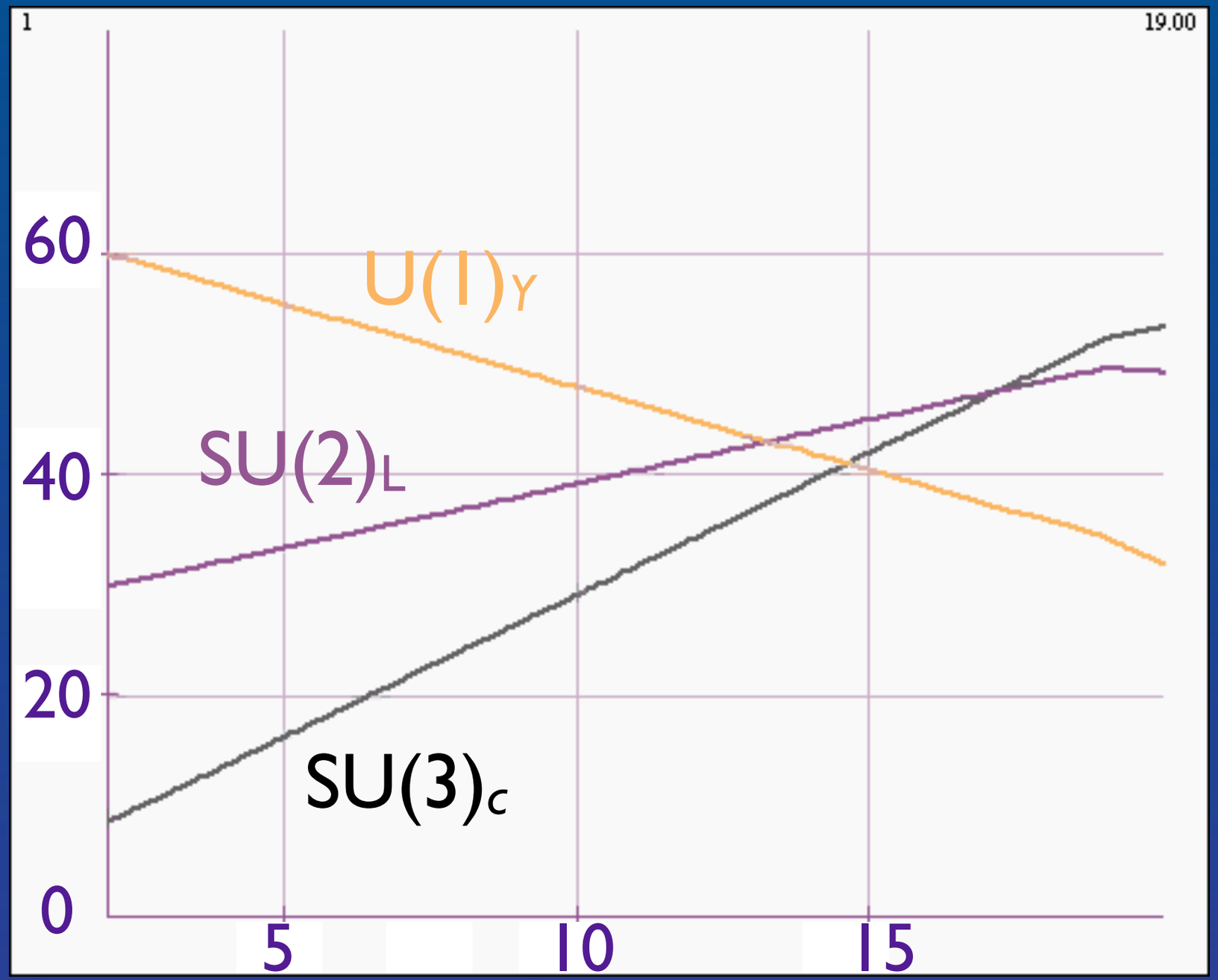
Revolution:

The Unity of Quarks & Leptons

- ▷ What do quarks and leptons have in common?
- ▷ Why are atoms so remarkably neutral?
- ▷ Which quarks go with which leptons?
- ▷ Quark-lepton extended family $\rightsquigarrow$ proton decay:
SUSY estimates of proton lifetime $\sim 5 \times 10^{34}$ y
- ▷ Unified theories $\rightsquigarrow$ coupling constant unification
- ▷ Rational fermion mass pattern at high energy?
(Masses run, too)

Evolution of the strong coupling "constant"




1
19.00
60
40
20
0
5
10
15
$U(1)_Y$
$SU(2)_L$
$SU(3)_c$
$1/\alpha$
$\log_{10}\left(\frac{E}{1\ \mathrm{GeV}}\right)$

Why is empty space so nearly massless?

Natural to neglect gravity in particle physics

Gravitational ep interaction $\approx 10^{-41}$ EM

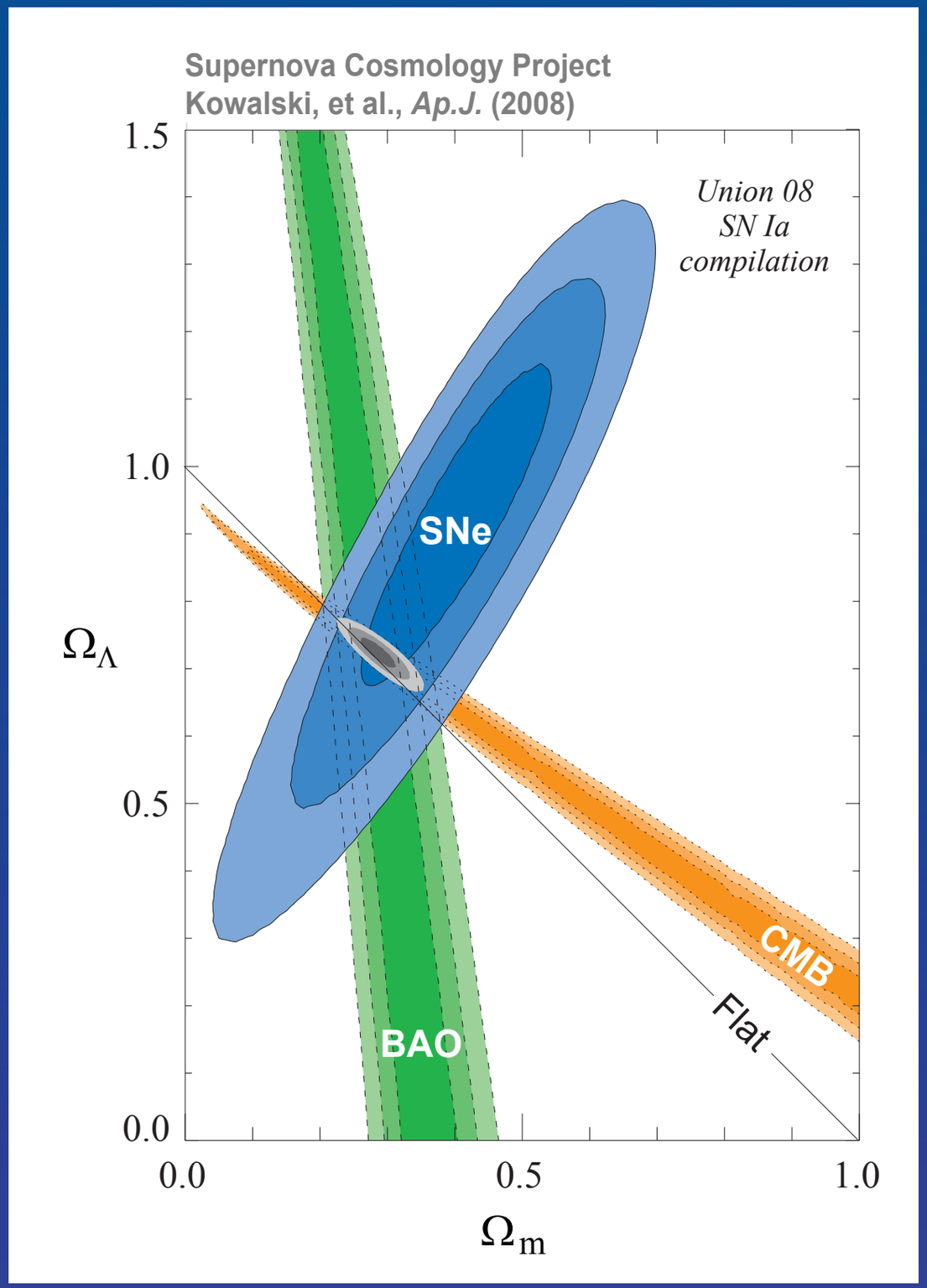
But gravity is not always negligible …

Higgs field contributes uniform vacuum energy density

$$\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8 \text{ GeV}^4 \quad \approx 10^{28} \text{ g/liter}$$

Critical density $\varrho_c \equiv \dfrac{3H_0^2}{8\pi G_{\text{Newton}}} \lesssim 10^{-26}$ g/liter

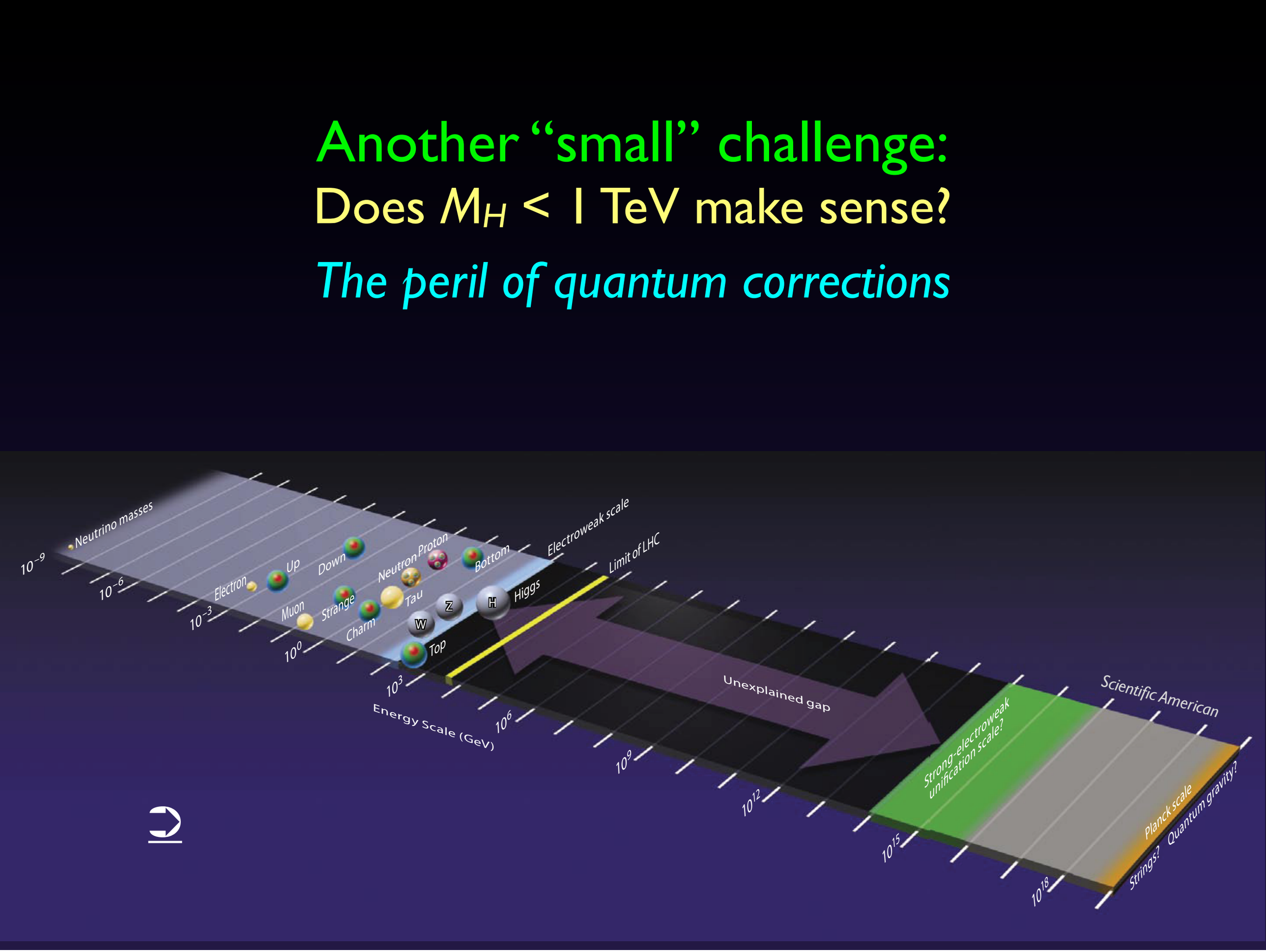
A chronic dull headache for thirty years …



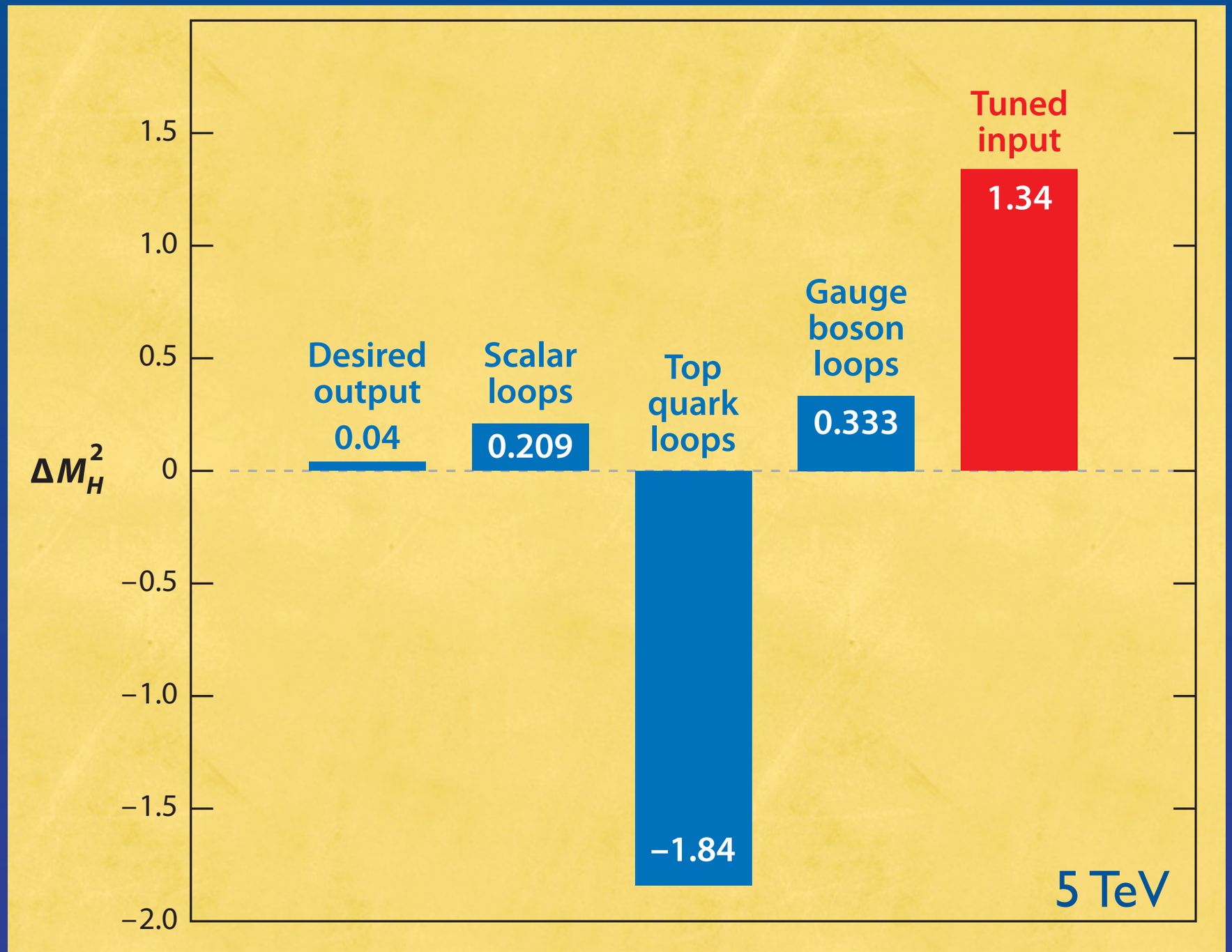
Another "small" challenge:

Does M_H < 1 TeV make sense?

The peril of quantum corrections



How to separate EW, higher scales?



How to separate electroweak, higher scales?

Extend electroweak theory on the 1-TeV scale …

composite Higgs boson

technicolor / topcolor

supersymmetry

. . .

Ask instead why gravity is so weak

Revolution:

A New Conception of Spacetime

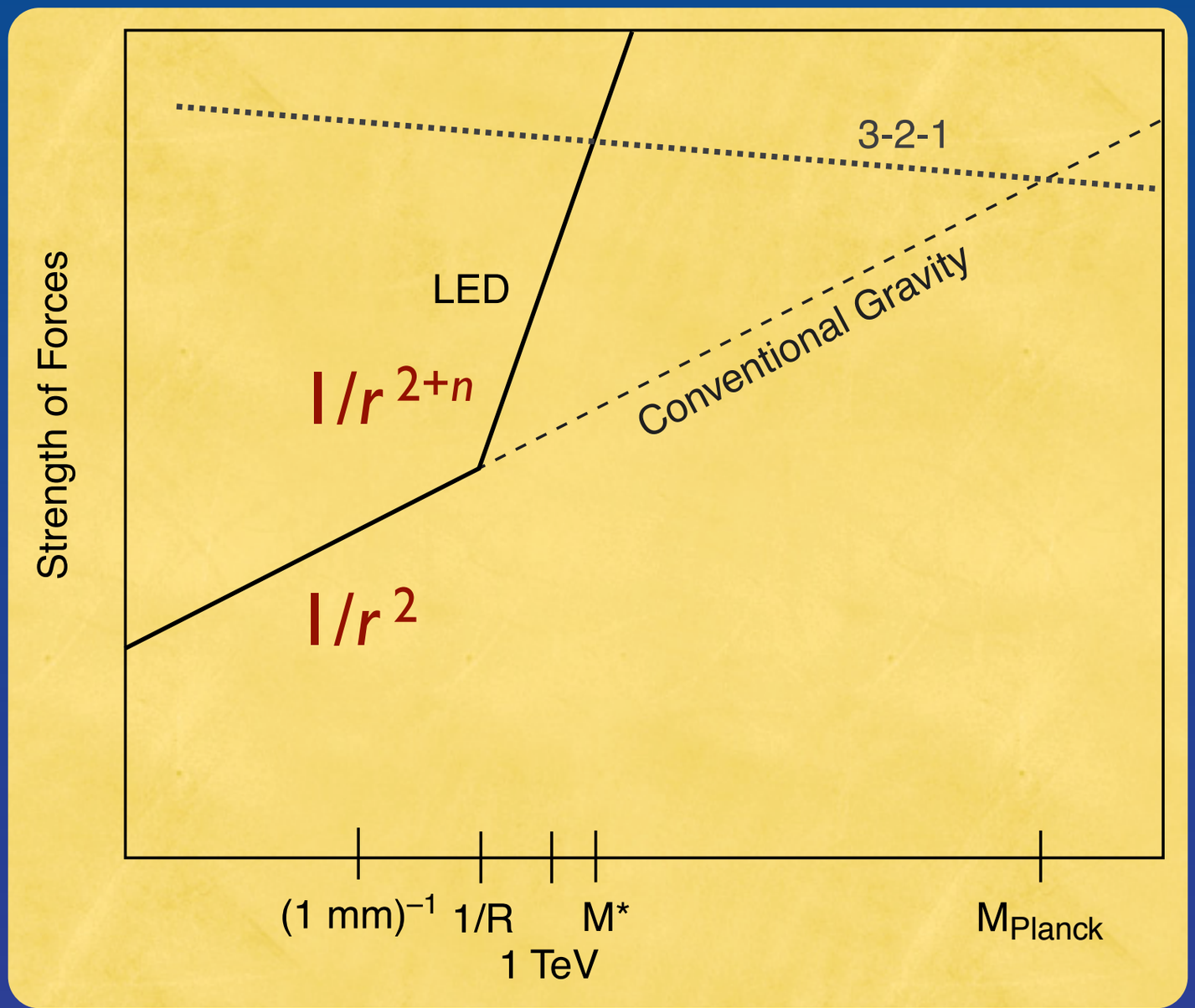
▷ Could there be more space dimensions than we have perceived?

- ▷ What is their size? Their shape?
- ▷ How do they influence the world?
- ▷ How can we map them?

string theory needs 9 or 10

Suppose at scale *R* … gravity propagates in 4+*n* dimensions

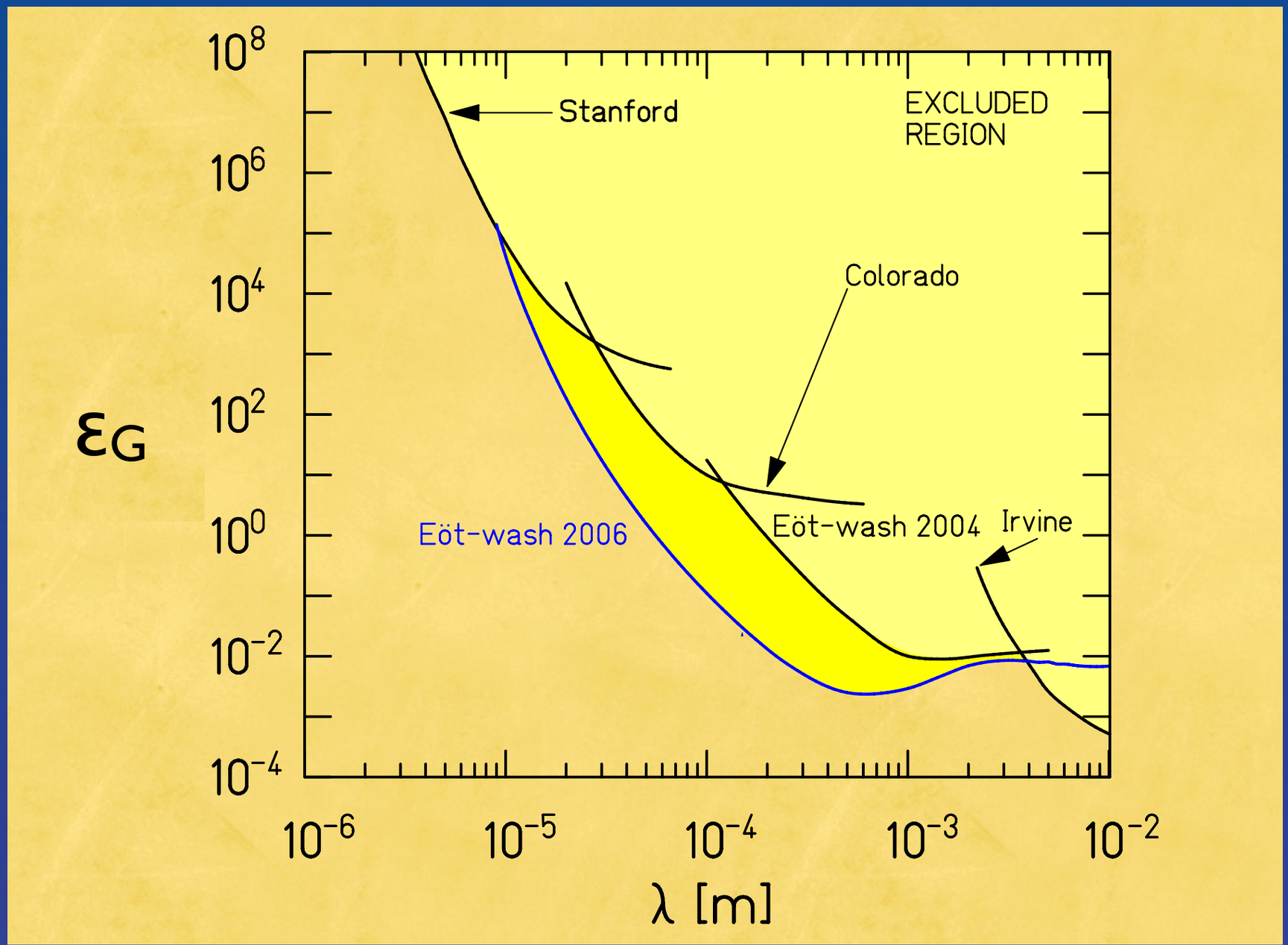
Gauss law: $G_N \sim M^{*-n-2}\ R^{-n}$ M^* : gravity's true scale



M_{Planck} would be a mirage!

Gravity follows Newtonian force law down to ≲ 1 mm

$$V(r) = -\int dr_1 \int dr_2 \frac{G_{\text{Newton}}\rho(r_1)\rho(r_2)}{r_{12}}\left[1 + \varepsilon_{\text{G}}\exp(-r_{12}/\lambda_{\text{G}})\right]$$



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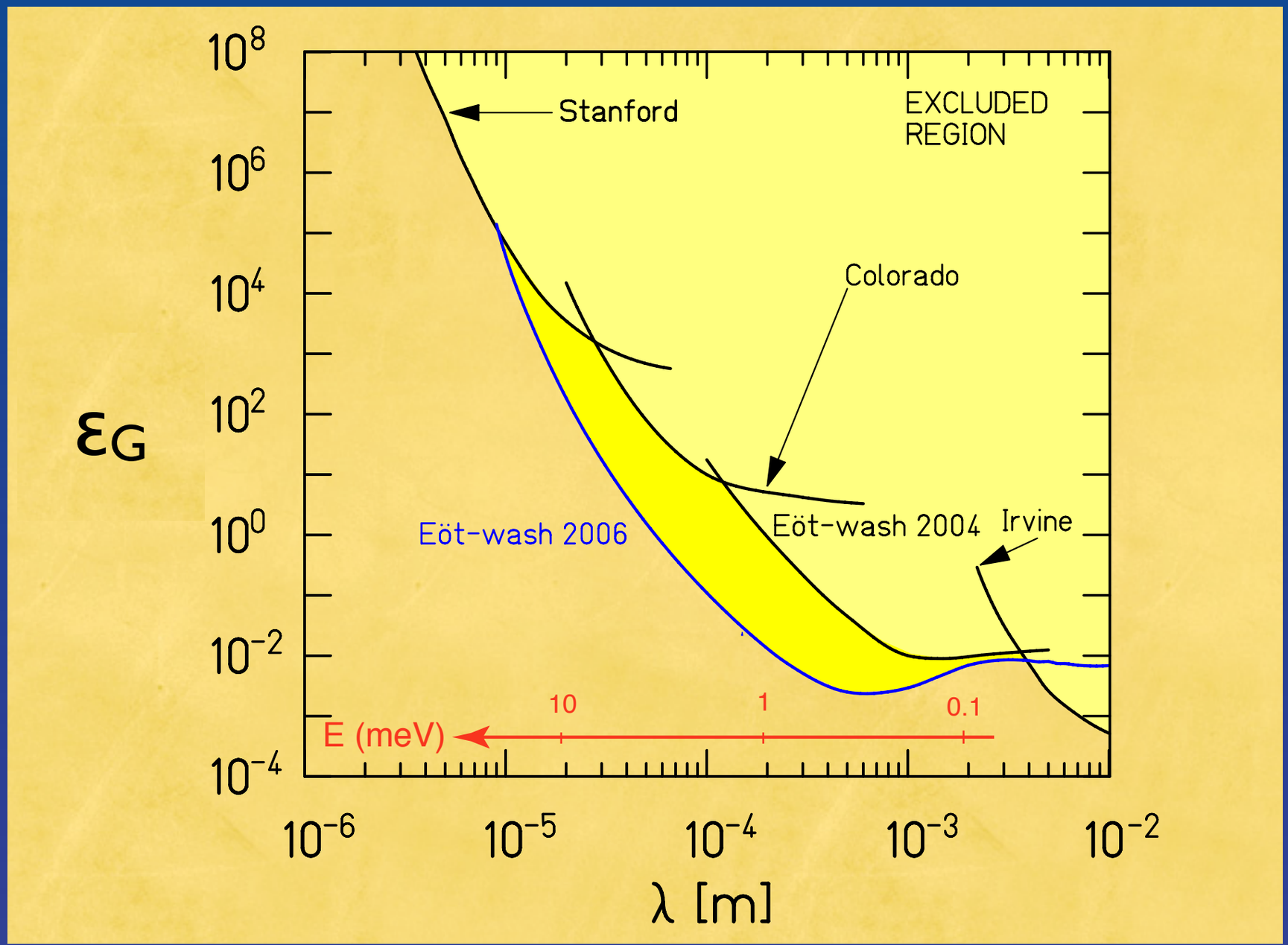

Connections …

arXiv:0905.3187

Scientific American, 2.2008